

Rowan University

Rowan Digital Works

Theses and Dissertations

10-31-2003

School bus idling and mobile diesel emissions testing: effect of fuel type and development of a mobile test cycle

Jason Scott Hearne
Rowan University

Follow this and additional works at: <https://rdw.rowan.edu/etd>



Part of the [Mechanical Engineering Commons](#)

Let us know how access to this document benefits you - share your thoughts on our feedback form.

Recommended Citation

Hearne, Jason Scott, "School bus idling and mobile diesel emissions testing: effect of fuel type and development of a mobile test cycle" (2003). *Theses and Dissertations*. 1319.
<https://rdw.rowan.edu/etd/1319>

This Thesis is brought to you for free and open access by Rowan Digital Works. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Rowan Digital Works. For more information, please contact LibraryTheses@rowan.edu.

**School Bus Idling and Mobile Diesel Emissions Testing: Effect
of Fuel Type and Development of a Mobile Test Cycle**

Jason Scott Hearne

A THESIS

PRESENTED TO THE FACULTY

OF ROWAN UNIVERSITY

IN CANDIDACY FOR THE DEGREE

OF MASTER OF SCIENCE

RECOMMENDED FOR ACCEPTANCE

BY THE DEPARTMENT OF MECHANICAL ENGINEERING

COLLEGE OF ENGINEERING

October 2003

School Bus Idling and Mobile Diesel Emissions Testing: Effect of Fuel Type and Development of a Mobile Test Cycle

Prepared by:

Jason Scott Hearne

Approved by:

Professor Anthony J. Marchese

Rowan University

Thesis Advisor

Professor Robert P. Hesketh

Rowan University

Thesis Reader

Professor H. Clay Gabler

Rowan University

Thesis Reader

Professor John C. Chen

/Chair, Mechanical Engineering

Rowan University

© Copyright by Jason Hearne, 2003. All rights reserved.

ABSTRACT

The New Jersey Department of Transportation (NJDOT) is currently sponsoring a research study at Rowan University to develop strategies for reducing diesel emissions from mobile sources such as school buses and class 8 trucks (classified as a heavy-duty truck of more than 33,000 lbs.). This thesis presents the results of an investigation performed to measure school bus idle emissions in a controlled environmental chamber. This thesis also presents the results of mobile school bus testing that has been performed to quantify the emission reduction capabilities of various alternative fuels, such as biodiesel, ultra low sulfur diesel, and a blend of the two, when used to fuel school buses that are representative of those currently in use in the state of NJ.

To measure emissions from school buses during idling conditions, three school buses equipped with an International T444E, an International DT466E, and a Cummins 5.9L B series engine were instrumented and tested at the Aberdeen Test Center at the Aberdeen Proving Grounds in Maryland. To simulate a wide variety of idling situations, tests were conducted at four different ambient temperatures (20°F, 40°F, 65°F and 85°F) and relative humidity ranging from 37 to 90%. In addition to quantifying school bus emissions during idling conditions, another objective of the school bus idling experiments was to develop a NO_x humidity correlation for use in mobile school bus emissions testing, the first phase of which is presented herein. The results of the idle testing provide evidence that the measured CO emissions decrease from 10% to 40% with increasing ambient temperature. The measured NO_x emissions under similar conditions vary by school bus and therefore a single correlation could not be developed that accurately corrects NO_x emission for all three buses. Rather, an engine specific correction factor was developed for each school bus engine. The results also show that current NO_x correction standards fail at lower temperatures suggesting that caution should be used when performing mobile emissions testing.

To ensure repeatability of testing under conditions that accurately reproduce actual school bus operating conditions, a new composite mobile school bus cycle was developed. The cycle was developed by acquiring Global Positioning System (GPS) data from actual school bus routes from 5 different municipalities within the state of New

Jersey.

For both the mobile and idle tests, exhaust gas emission measurements were made using a Sensors Semtech-D to measure CO, CO₂, NO₂, NO, O₂, and HC, along with a Sensors PM-300 to measure Particulate Matter. In addition to the exhaust emissions measurements, operating parameters such as instantaneous vehicle speed, engine speed, percent load and fuel flow rate were acquired from the engine electronic control module (ECM) during testing.

The mobile emissions results presented in this thesis focus mainly on a comparison of alternative fuels on mobile emissions acquired during the new mobile test cycle that was developed as part of this study. The results of the mobile testing prove that the Rowan University Composite School Bus Cycle (RUCSBC) is a repeatable mobile test cycle when run during the same operating conditions. The results of mobile testing show a decrease in HC emissions for the alternative fuels tested for all buses of 7% to 43%. NO_x emissions were only slightly affected by alternative fuels by 0% to 10%. A 20% biodiesel blend and ultra low sulfur diesel reduced CO and PM emissions by 30% to 40% for the T444E and Cummins, but showed no affect on the DT466E bus. The ultra low sulfur diesel and biodiesel blend provided significant reductions in CO and PM by 70% and 50%, respectively, for the T444E and a 22% reduction in PM for the DT466E.

Finally, in addition to the tests conducted at the Aberdeen Testing Center (ATC), a series of on-road tests were performed using school buses presently in service on actual operating routes. Specifically, four International DT466E school buses were tested at the Medford, New Jersey School District, a district that has been operating half of their school bus fleet on biodiesel for the past five years.

For Mom and Dad, Family, and Danielle.

ACKNOWLEDGEMENTS

My sincerest thanks to my graduate advisors, Dr. Anthony Marchese and Dr. Robert P. Hesketh. This thesis could not have been completed without their knowledge, support, and guidance throughout the entire project. Also I would like to extend extreme appreciation to the project sponsor, NJDOT, and project manager Henry Schweber. Added thanks to Dr. Gabler and Dr. Hesketh for reading this thesis. I would also like to thank all of the Aberdeen, Maryland testing staff, especially Todd Morris (T' Mo) for all he contributed to the project.

I would also like to thank Gil and Carol Hearne, my parents, and the rest of my family for understanding that time away from home was well spent. A special thanks goes out to my friends for their continued support, especially my Holly Court roommate Lew Clayton, my officemate Doug Gabauer, my teammate Andy Toback, and my overseas warrior Dan Peterson. And finally, I would like to thank my beautiful and loving girlfriend Danielle Baldwin, who has kept me in line for the over a year now and will hopefully continue to do so.

TABLE OF CONTENTS

Abstract.....	iv
Dedication.....	vi
Acknowledgments.....	vii
Table of Contents.....	viii
List of Figures.....	xi
List of Tables.....	xiii
1. Introduction.....	1
1.1. Background.....	1
1.2. Literature Search.....	3
1.3. Goal of Study.....	6
1.3.1. Project Sponsor NJDOT.....	6
1.3.2. State Implementation Plan.....	6
1.3.3. Project Research Team - Rowan University.....	7
1.4. Emissions/ Emission Measurement.....	8
1.4.1. Diesel Emissions.....	8
1.4.2. EPA Diesel Emissions Regulation History.....	10
1.4.3. Units of Measure for Emissions.....	13
1.4.4. Emissions Testing.....	15
1.4.4.1. Engine Dynamometer Emissions Testing.....	15
1.4.4.2. Chassis Dynamometer Emissions Testing.....	17
1.4.4.3. Mobile In-Use Emissions Testing.....	20
1.5. Diesel Emission Reduction Strategies.....	22
1.5.1. Alternative Fuels.....	23
1.5.2. Particulate Traps.....	26
1.6. Thesis Organization.....	30
2. Experimental Procedure and Equipment.....	32
2.1. Introduction.....	32
2.2. Rationale for School Bus Selection.....	32
2.2.1. School Bus Types in NJ.....	32
2.2.2. Engine Specifications.....	35
2.2.2.1. 1997 International T-444E.....	35
2.2.2.2. 1997 International DT-466E.....	36

2.2.2.3.	1996 Ford Cummins 5.9 L ISB Series	37
2.3.	Aberdeen Test Center	41
2.3.1.	Test Track	41
2.3.2.	Environmental Testing Chamber	41
2.3.3.	Chemistry Lab.....	42
2.4.	Bus Instrumentation	43
2.4.1.	Instrumentation Table	44
2.4.2.	Electronic Control Module (ECM)	45
2.4.3.	Sensors Inc. Semtech-D	47
2.4.4.	Sensors Inc. PM-300.....	56
2.4.5.	ADOCS ATC Data Acquisition System	58
2.4.6.	Data Management	59
3.	Development of a New Mobile Emissions Test Cycle for School Buses.....	61
3.1.	Introduction.....	61
3.2.	Literature Review.....	62
3.3.	Procedure for Generating a New Mobile Cycle.....	66
3.3.1.	Types of School Districts /Regions.....	67
3.3.2.	GPS Mapping: Experimental Procedure	70
3.3.3.	Data Reduction/Cycle Development.....	73
4.	Rowan On Road Medford Township School Bus Testing.....	81
4.1.	Introduction.....	81
4.2.	Purpose of Medford Study	81
4.3.	Medford School District Biodiesel Program.....	82
4.4.	Experimental Setup: Test Procedure.....	84
4.5.	Test Results.....	85
4.5.1.	Medford Fuel Consumption/Total Work	85
4.5.2.	Medford Emissions	88
5.	School Bus Idle Emissions.....	93
5.1.	Introduction.....	93
5.2.	Literature Search.....	94
5.2.1.	HDDV Study.....	94
5.2.2.	School Bus Idling.....	96
5.3.	Experimental Procedure: Test Matrix	96
5.4.	Test Results.....	99
5.4.1.	Fuel consumption.....	99
5.4.2.	Emissions	100

5.4.2.1.	CO ₂ Emissions	102
5.4.2.2.	CO Emissions.....	103
5.4.2.3.	NO _x Emissions	104
5.4.2.4.	HC Emissions.....	106
5.4.2.5.	PM Emissions	107
5.4.2.6.	Experimental Results – NO _x correction.....	108
6.	School Bus Mobile Emissions Testing (ATC).....	114
6.1.	Introduction.....	114
6.2.	Experimental Procedure: Test Matrix.....	114
6.3.	Test Results.....	115
6.3.1.	Raw data and NO _x Correction Factors.....	117
6.3.2.	T444E Emissions	120
6.3.3.	DT466E Emissions	122
6.3.4.	Cummins 5.9L Emissions	124
6.3.5.	Mobile Emission Test Results (g/bhp-hr)	126
7.	Conclusions and Future Work	128
7.1.	Conclusions.....	128
7.1.1.	Idle	128
7.1.2.	Mobile.....	129
7.1.3.	Thesis	130
7.2.	Future Work.....	131
8.	References.....	133

LIST OF FIGURES

Figure 1: US EPA Emissions Standards Timeline for HDDV's for NO _x and HC	12
Figure 2: US EPA Emissions Standards Timeline for HDDV's for PM.....	13
Figure 3: Engine dynamometer in-use	17
Figure 4: Water brake dynamometer installed in ground	19
Figure 5: Schematic of a diesel particulate filter	27
Figure 6: Johnson Matthey CRT diesel particulate filter.....	28
Figure 7: International T-444E diesel engine	36
Figure 8: International DT-466E diesel engine	36
Figure 9: Cummins 5.9 L B Series diesel engine.....	37
Figure 10: T-444E engine lug curve	38
Figure 11: DT-466E engine lug curve	39
Figure 12: Cummins 5.9 L engine lug curve	40
Figure 13: Environmental testing chamber 4.....	42
Figure 14: Sensors inc. Semtech-D mobile emissions analyzer	48
Figure 15: Internal layout of Semtech-D unit ⁵⁴	48
Figure 16: Sensor's Inc. PM-300 particulate analyzer	57
Figure 17: Excel graph of PM data separated by bins	58
Figure 18: ADvanced Onboard Computer System (ADOCS).....	59
Figure 19: City Suburban Heavy Vehicle Route	64
Figure 20: Central Business District Cycle.....	66
Figure 21: New Jersey Population Breakdown by Urban and Rural Regions ⁶²	70
Figure 22: Garmin GPSMAP76S.....	71
Figure 23: Pittsgrove Township GPS Map	72
Figure 24: Pittsgrove School District velocity vs. time profile	73
Figure 25: The Rowan University Composite School Bus Cycle.....	77
Figure 26: Rowan University Cycle Separated by Representative Regions.....	77
Figure 27: Speed Trace of Two Separate Runs of the RUCSBC	79
Figure 28: Speed Trace of Two Separate Runs of the RUCSBC (Reduced Axis)	79
Figure 29: NO _x Concentration Trace of Two Separate Runs of the RUCSBC	80

Figure 30: NO _x Concentration Trace of Two Separate Runs of the RUCSBC (Reduced Axis).....	80
Figure 31: Medford Township's biodiesel operated school bus fleet.....	83
Figure 32: Medford biodiesel storage tank	83
Figure 33: Speed Trace of Simulated Medford School Bus Route.....	85
Figure 34: Fuel Consumption for Medford school buses tested	85
Figure 35: Work for Medford school buses tested.....	87
Figure 36: Fuel Consumption as a function of work for Medford school buses tested	88
Figure 37: Average emissions results for the 4 different Medford buses tested.....	90
Figure 38: Typical NO _x emissions during a test	98
Figure 39: Fuel consumption rates for the three buses tested.	100
Figure 40: Measured CO ₂ emissions during idling for school bus with DT466E engine.	102
Figure 41: Effect of ambient temperature on CO emissions.....	103
Figure 42: NO _x emissions during idling conditions for school bus with T444E engine.	104
Figure 43: NO _x emissions during idling conditions for school bus with DT466E engine.	105
Figure 44: NO _x emissions during idling conditions for school bus with Cummins 5.9 L engine.	105
Figure 45: Effect of ambient temperature on HC emissions.....	106
Figure 46: Uncorrected NO _x emissions (ppm) for the school bus with DT466E engine.	110
Figure 47: Corrected NO _x emissions using the SAE J1243 correction factor.	111
Figure 48: Corrected NO _x emission data using the CFR40 86.1342-90.....	111
Figure 49: Engine specific corrected NO _x emissions for the DT466E.	112
Figure 50: Raw emissions data from RUCSBC.....	116
Figure 51: Raw NO _x emissions data correction factor comparison for T444E	118
Figure 52: Average mobile emissions results for the International T444E	121
Figure 53: Average mobile emissions results for the International DT466E	123
Figure 54: Average mobile emissions results for the Cummins 5.9L.....	125

LIST OF TABLES

Table 1: Gross Vehicle Weight Rating (GVWR) for diesel trucks.	9
Table 2: EPA Emission Standard History for HDDV's.....	13
Table 3: Engine types used in NJ School Districts.....	33
Table 4: Engine selection for school bus emissions testing.....	35
Table 5: School bus emissions testing instrumentation.	44
Table 6 Prototypical NJ School Bus Districts ⁶² ,	69
Table 7: Statistical Information on Microtrip Categories	74
Table 8: Microtrip Times for a Cycle with a Minimum of 20 Minutes.....	76
Table 9: Vehicle and engine data for Medford school buses investigated.	84
Table 10: Medford fuel consumption and work	88
Table 11: Vehicle and testing condition parameters for the four different Medford buses tested.....	89
Table 12: Average emissions results for the four different Medford buses tested measured in g/mile.....	89
Table 13: Average emissions results for the four different Medford buses tested measured in g/bhp-hr and ppm concentration	89
Table 14: Environmental test matrix for each bus	97
Table 15: Emission results from environmental chamber testing.....	101
Table 16: Average PM for the three bus engines tested	107
Table 17: Engine specific values for SAE 1243 correlation.....	113
Table 18: Test matrix for each school bus	115
Table 19: Fuel properties for fuels tested at ATC.....	116
Table 20: Average concentrations and various NO _x corrections for T444E	118
Table 21: Average concentrations and various NO _x corrections for DT466E.....	119
Table 22: Average concentrations and various NO _x corrections for Cummins.....	120
Table 23: Alternative fuel reductions in emission levels when compared to #2 diesel..	122
Table 24: Alternative fuel reductions in emission levels when compared to #2 diesel..	124
Table 25: Alternative fuel reductions in emission levels when compared to #2 diesel..	126
Table 26: Comparison of test results with 2007 standards	127

1. Introduction

1.1. Background

It is estimated that heavy-duty diesel vehicle (HDDV) emissions are responsible for 80 % of all particulate matter (PM) emissions and 33 % of all NO_x emissions from mobile sources in the northeast United States.¹ Accordingly, the New Jersey Department of Transportation (NJDOT) Bureau of Transportation Technology is developing emission reduction strategies aimed at reducing harmful emissions from diesel engines in the state of New Jersey. The NJDOT is currently focusing on three areas of concern with respect to harmful emissions from diesel engines:

- Reduction of emissions from school buses
- Development of low exhaust gas temperature catalytic converter technologies
- Reduction of idling time by interstate carriers (HDDV diesel trucks).

During each school year, about 23.5 million students travel approximately 4.3 billion miles on 450,000 school buses in the United States.² Of the 450,000 school buses in the U.S, 390,000 are powered by diesel fuel.³ Diesel school bus routes produce pollutants in the form of nitrous oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons (HC), volatile organic compounds (VOC), and particulate matter (PM), which may be avoidable with the use of alternative fuels and the addition of engine retrofit emission reduction after treatment devices. In addition to the emissions produced by the 4.3 billion school bus miles traveled each year, there are several minutes (possibly hours depending on weather conditions and other factors) of idling time daily that all school buses will incur on a typical route. Reduction of school bus emissions is particularly important because children are the most susceptible to the effects of diesel

emissions, which can cause respiratory disease and bring about long-term conditions such as asthma.³

The current emissions regulations for school buses are lenient enough that newer school buses are able to operate legally with no after treatment devices or alternative fuels sources. In 2004 and again in 2007, more stringent emission standards are being put in place by the federal government that will mandate the use of some after treatment for new HDDV's in order to meet the new standards. NJ regulations that mandate school buses to be in service for a maximum of twelve years allows for school bus engines manufactured before 2007 to possibly remain in service until 2019 without complying with the 2007 standards. Many state organizations, engine manufactures, universities, and research facilities are conducting research projects to find the most inexpensive and effective way to meet the new standards before they are put into place in the upcoming years.

This thesis presents results of an experimental study aimed at evaluating emission reduction strategies for diesel powered school buses. Three school buses, which were purchased by NJDOT, were instrumented and tested at the U.S. Army Aberdeen Test Center (ATC). The most advanced mobile emission measurement equipment was purchased to measure the harmful emission levels from the school buses. The school buses were tested using a mobile test cycle, developed as part of the study and described in this thesis.

There is currently a lack of mobile testing cycles for school buses, so a NJ composite school bus mobile testing cycle, the Rowan University Composite School Bus Cycle (RUCSBC) was created for the testing. A variety of fuel types were tested to determine

the cleanest burning fuel type for the NJ school bus duty cycle (e.g. rural, urban, etc.) that was developed. Previous research in the heavy-duty diesel emission reduction field has been conducted in research labs on engine and/or chassis dynamometers. Testing for this project was conducted entirely with the vehicle mobile or on-road on a test track at the Aberdeen Testing Center running the RUCSBC. Another important aspect of this research is to gain an understanding on how temperature and humidity effects emissions, specifically NO_x. In the following section, a review of prior literature is presented.

1.2. Literature Search

In recent years several experimental and theoretical studies have been performed on diesel emission reduction strategies. Each of these studies has focused on emission reduction strategies by performing tests on a chassis or an engine dynamometer. The majority of previous studies were mainly performed on different HDDV's other than school buses. The few previous studies on school buses did not use testing cycles that were initially developed for school bus operation. This thesis presents the results of a new experimental mobile emission reduction study using a newly developed school bus mobile testing cycle. A review of several previous emissions studies is provided in the following sections.

As stated previously, there has been only a limited number of school bus emission studies ever reported in the literature. One of the first school bus emissions studies took place in 1978 and evaluated tailpipe CO emissions only.⁴ In this earlier study, school buses were tested for CO levels over a 10-month evaluation period to determine whether or not there were any serious CO intrusion problems or indications of potential problems on a small sample of the nation's school buses. Test results from the study showed, based

on a maximum safe exposure level of 20 ppm, that 7.2% of the buses tested exceeded this level, and 5.4% of the buses tested had maximum CO readings over 50 ppm.

In 1995, the Northeast Florida Regional Planning Council, together with the National Biodiesel Board compared four alternative fuel sources to # 2 diesel in one of the sector school bus fleets.⁵ These tests did not consider varying weather conditions or any direct comparison of a bus running identical cycles. The alternative fuels tested in this study were: biodiesel (B20 and B100), compressed natural gas (CNG), liquefied natural gas (LNG) and liquefied petroleum gas (LPG). The study concluded that relative to diesel, each of the four fuels tested had significantly lower emissions. B20 reduced CO and PM by 12 % and HC by 20 %. B100 reduced CO and PM by 50 % and HC by 70 %. This study also showed biodiesel resulted in significant reductions of unburned HC, CO, and PM. NO_x emissions stayed the same or were slightly increased. The study concluded that biodiesel blends could compete effectively with other alternative fuels when life cycle, total fleet costs are considered.

Another study conducted in 1997, and followed up in 1999, evaluated diesel emissions, from a variety of vehicle classes several of which were school buses. The study evaluated the initial effects of a retrofitted diesel oxidation catalyst technology and also the effects of the device two-years later. In this study chassis dynamometer emissions testing and in-use emissions testing were employed with and without a retrofitted catalyst technology using the New York Composite and Central Business District cycles, further detailed in Chapter 3.⁶ The results of the study found that the diesel oxidation catalyst reduced total PM by 20 to 50 %, CO by 45 to 93 %, and HC by 50 to 90 %.

In another study, West Virginia University characterized the emissions of a fleet of school buses in Indio, Ca. In this fleet, both 8.3 L Cummins natural gas engines and conventional 8.3 L diesel engines were tested. Their results showed that the natural gas engines had lower emissions in PM and NO_x (46 % and 12 %, respectively), but higher emissions of HC (50 %) compared to the diesel engine.⁷ A remote sensing study of CO and HC emissions from school buses was initiated to develop emissions factors but results of this study have not been reported.⁸

The most recent study involving school buses was completed by collaboration between ARCO, West Virginia University, Johnson Matthey, and Engelhard.⁹ The program evaluated ultra-low-sulfur diesel fuels and passive diesel particulate filters (DPFs) in truck and bus fleets operating in southern California. In this study exhaust emissions, fuel economy and operating cost data were collected for the test vehicles, and compared with baseline control vehicles. The evaluation of exhaust emissions took place prior to testing and also one year after installation of the filters. For all fleets tested including school buses, the test vehicles retrofitted with the DPFs reduced PM emissions by more than 90% when operated on ULSD when compared to the control vehicles having factory mufflers and operated on a typical California diesel fuel.

The San Diego School Bus Pilot program is currently testing 30 school buses. Five of the 30 buses are equipped with the Johnson-Matthey CRT filter and the other five buses are fitted with the competing Engelhard DPX filter technology. The second part of the California school bus pilot program is using a test fleet of 39 school buses from the Los Angeles Unified School District, the Anaheim Union High School district, and the Hemet Unified School district. In this program, 13 buses have been retrofitted with Johnson-

Matthey CRT filter system, thirteen buses retrofitted with Englehard DPX filter technology and at least one with Ceryx Quadcat system. The remaining buses are using low-sulfur ECD diesel fuel and no filter system.¹⁰

1.3. Goal of Study

1.3.1. Project Sponsor NJDOT

NJDOT is committed to the support and implementation of air quality friendly transportation projects and programs and is continually looking for new strategies and initiatives that could provide emission reduction benefits. Through studies conducted by various agencies, NJDOT recognizes the potential value of the reduction of mobile and idle emissions from school buses in its efforts to support and implement air quality friendly projects. A grant from NJDOT is responsible for the work conducted on the emission reduction study by a team of Rowan University faculty and students.

1.3.2. State Implementation Plan

In response to the Section 109 of the Clean Air Act, the US Environmental Protection Agency (USEPA) established the National Ambient Air Quality Standards (NAAQS). The NAAQS monitors various pollutants, known as “criteria” pollutants, which adversely affect human health (primary) and welfare (secondary). The primary and secondary transportation-related criteria pollutants include Ozone (O₃) and its precursors, lead, volatile organic compounds (VOC) and oxides of nitrogen (NO_x), particulate matter (PM), sulfur dioxide (SO₂), and carbon monoxide (CO).

Each state is required to submit to the EPA a State Implementation Plan or SIP, which is a collection of strategies/ commitments that explain how the State will achieve the air quality standards, set by the Federal Clean Air Act. In New Jersey, the Department of

Environmental Protection (NJDEP) is the agency responsible for assembling and submitting the SIP to the USEPA. The SIP includes strategies and commitments for stationary (factories, etc) and mobile (on and off-road vehicles, auto inspections, etc.) sources. The New Jersey Department of Transportation (NJDOT) provides input to the mobile source portion of the SIP.

New Jersey is regulated under region 2 air quality standards, which also includes New York, Puerto Rico, and the Virgin Islands. Region 2 is one of the most urban regions found in the United States. Approximately 30 million residents are concentrated in the Region 2 urban areas, in which 85 percent of the 30 million live in New York and New Jersey, mainly in the New York - New Jersey metropolitan area¹¹. When the NJDEP produces a draft of the SIP that contains proposed strategies for improved air quality they first propose the SIP in a public process. The next step is to formally adopt the SIP and submit it to the USEPA for approval to the Code of Federal Regulations (Title 40, Part 52)¹². After approval by the USEPA the state's SIP becomes federally enforceable.

1.3.3. Project Research Team - Rowan University

The main goal of the Rowan University research team was to provide NJDOT with adequate results to formulate an effective SIP. The project also will act as a foundation for future emission related projects presented to Rowan University in the future. The Rowan University research team was responsible for researching emissions reduction literature, obtaining the test vehicles, researching reduction strategies, providing testing instrumentation and the reduction strategies, analyzing the data collected from the ATC personnel testing the buses, and finally recommending the most effective emission reduction strategies to the NJDOT. To date the project has produced two master theses

for Rowan Engineering graduate students, five Society of Automotive Engineers (SAE) conference papers, and provided an engineering clinic projects for eleven undergraduate students for three semesters. During this time, students were given the opportunity to travel to a remote testing facility at the U.S. Army Aberdeen Test Center where instrumentation and testing of the school buses occurred.

1.4. Emissions/ Emission Measurement

This research focuses on the EPA regulated emissions from HDDV's: CO, NO_x, HC, and PM. In addition, the greenhouse gas CO₂ is also examined. The EPA has regulated HDDV emissions since 1970, and has since slowly reduced the allowable level of each pollutant to the future standards of 2007. School buses stay in a school district's fleet for a maximum of 13 years by law, so by 2007 school buses from as early as 1994 could still be operating in a district's fleet. All emission testing takes place using a testing system such as an engine dynamometer, chassis dynamometer, or mobile in-use emissions. When testing using these different systems the units used to analyze the experimental data becomes an important factor in developing conclusions. The research presented herein, focuses on experimental data taken from mobile in-use emissions testing, however it should be noted that the other two methods of testing (engine and chassis) have advantages and disadvantages that are relevant to consider when forming conclusions.

1.4.1. Diesel Emissions

Mobile sources contribute significantly to air pollutants such as carbon monoxide CO, carbon dioxide CO₂, nitrogen oxide NO, nitrogen dioxide NO₂, particulate matter PM, and hydrocarbons HC. A mobile source is defined as any variety of vehicle, engine, or

equipment that generates air pollution and that moves, or can be moved, from place to place.¹³ A school bus falls into the mobile source emission category under a heavy-duty diesel vehicle (HDDV). A HDDV is any diesel-powered vehicle with a weight over 8,501 pounds Gross Vehicle Weight (GVW).¹³ HDDV's are divided into different classes (e.g. Class 7, Class 8, etc.) according to the weight of the vehicle, with Class 8 being the heaviest. School buses are typically rated as Class 7 or Class 8. The gross vehicle weight ratings (GVWR) according to class are shown in Table 1.

Table 1: Gross Vehicle Weight Rating (GVWR) for diesel trucks.

Vehicle	2B	3	4	5	6	7	8
GVWR (lbs.)	8,501 - 10,000	10,001 - 14,000	14,001 - 16,000	16,001- 19,500	19,501- 26,000	26,001- 33,000	33,000+

Carbon monoxide (CO) gas has no odor and is colorless. CO is produced by the incomplete combustion of the fossil fuels – gas, oil, coal and wood used in boilers, engines, oil burners, gas fires, water heaters, solid fuel appliances and open fires. Automobiles are the primary source of CO pollution. Transportation sources are responsible for 77% of the nationwide CO emissions.¹⁴ CO emissions increase when the weather is cold or when less oxygen is available in the air to burn the fuel (poor combustion). When the carbon in the fuel is fully oxidized rather than partially oxidized, the greenhouse gas carbon dioxide (CO₂) is formed. The EPA does not regulate CO₂ for HDDV's, however reducing the greenhouse CO₂ is still important for the environment. CO₂ could be reduced by making an engine's combustion process more efficient by regulating school bus idle time.

The emissions NO and NO₂ are often grouped into a single term to from the EPA

regulated emission NO_x , or oxides of nitrogen. The EPA regulates NO_x emissions as a whole and does not regulate individual oxides of nitrogen. NO_x emissions are produced during the combustion of fuels at high temperatures.¹⁴ NO_x is formed from a variety of mobile highway sources (e.g. HDDV's), non-road sources (e.g. marine and locomotives) and stationary sources (e.g. factories and power plants). Prior research has shown that at higher ambient and combustion temperatures there is an increase in NO_x . Hydrocarbons (HC) are produced differently with increasing combustion temperature than NO_x ; increasing combustion temperature will lower HC emissions. HC emissions result from when fuel molecules in the engine do not burn or burn only partially.

The final regulated emission by the EPA is particulate matter (PM). PM is microscopic particles or liquid droplets suspended in the air that can contain a variety of chemical components. Low combustion temperatures and non-stoichiometric oxygen conditions result in incompletely burned fuel, and various concentrations of particulates largely of carbon composition. These particulates consist of elemental carbon (EC), organic carbon (OC), metals from fuel and engines wear, and sulfates with bound water.^{15,16} The National Ambient Air Quality Standard (NAAQS) for particulates are divided into two size groupings. For particulate matter less than $10\text{ }\mu\text{m}$, the NAAQS limits the annual average of particulates to $50\text{ }\mu\text{g}/\text{m}^3$ and the 24 hour average to $150\text{ }\mu\text{g}/\text{m}^3$. For particulate matter $2.5\text{ }\mu\text{m}$ and smaller the NAAQS annual average is $15\text{ }\mu\text{g}/\text{m}^3$ and the 24 hour average is $65\text{ }\mu\text{g}/\text{m}^3$.

1.4.2. EPA Diesel Emissions Regulation History

Since diesel engine emissions have been classified by the International Agency for Research on Cancer as a Group 2A carcinogen (probably carcinogenic to Humans) the

EPA began regulating emissions.¹⁷ Since 1970 the EPA has been regulating certain emissions from HDDV (including school buses). The EPA regulates the following pollutants from mobile sources:

- Total Hydrocarbons (HC)
- Oxides of nitrogen (NO_x)
- Particulate matter (PM)
- Carbon monoxide (CO)

From 1970 to 1974 however, only opacity levels of smoke for acceleration and lugging (laboring the engine in too high a gear) were regulated. In 1974, CO and a combined HC + NO_x regulation were put into effect as well as tighter smoke standards. Combining HC and NO_x emissions were an attempt to ease the transition into regulated emissions for engine manufacturers. The CO limit was introduced at 40 g/bhp-hr and the HC + NO_x was introduced at 16 g/bhp-hr. The emissions standards again tightened in 1979 with CO emission levels tightened to 25 g/bhp-hr. Also in 1979, a choice of 5 g/bhp-hr HC + NO_x or HC of 1.5 g/bhp-hr combined with a 10 g/bhp-hr HC + NO_x was introduced for the first time.

In 1984 new regulations split NO_x and HC into individual standards. In 1988 particulate matter regulations were introduced for the first time and set at .60 g/bhp-hr. Starting in the early 1990's new engine technologies were needed to meet the tightening regulations. In 2004, HC and NO_x will again recombine to be regulated as one emission in an effort to make the most stringent emissions standards ever in 2007 possible for engine manufacturers and fleet owners to meet. Also it is important to note that in 2007, the sulfur content in fuel will be reduced from an average of about 500 ppm to 15 ppm,

which will also be helpful when using particulate traps that require ultra low sulfur fuel.

Figure 1 and Figure 2 show the EPA emission standard timelines from 1974 to model year 2007 for NO_x, HC, and a HC and NO_x combination and a timeline for PM, respectively. A complete listing of emission regulations since 1970 is shown in Table 2.

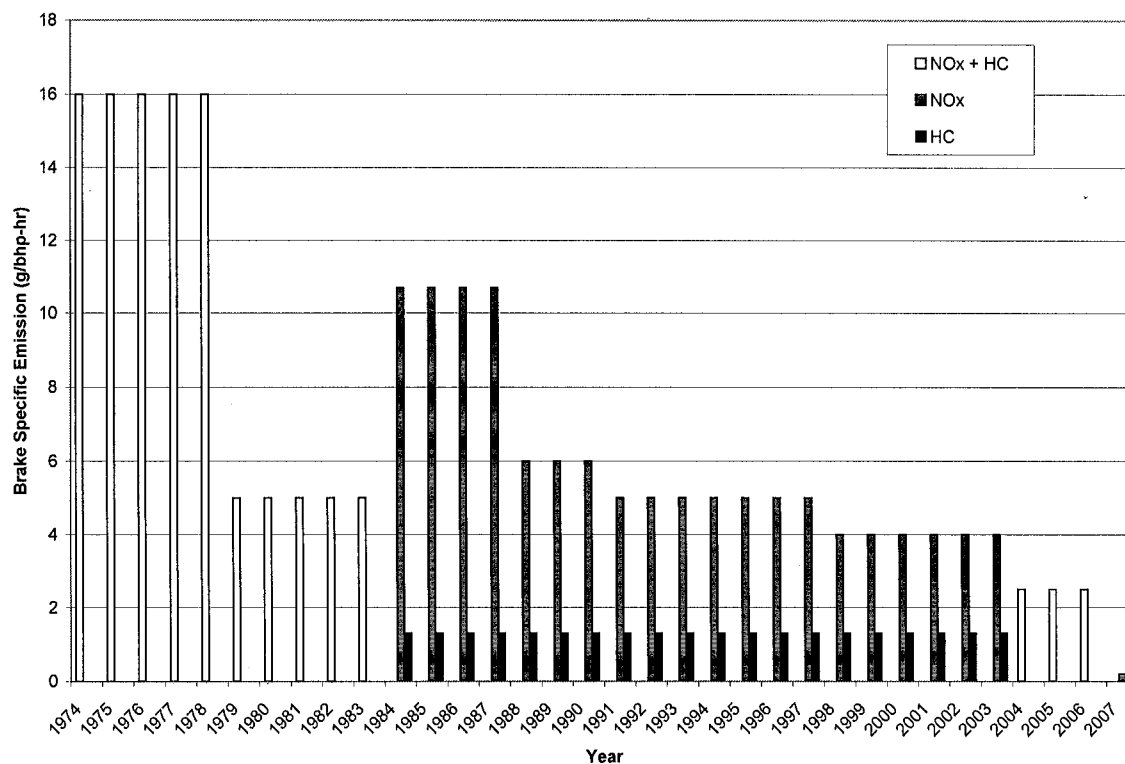


Figure 1: US EPA Emissions Standards Timeline for HDDV's for NO_x and HC

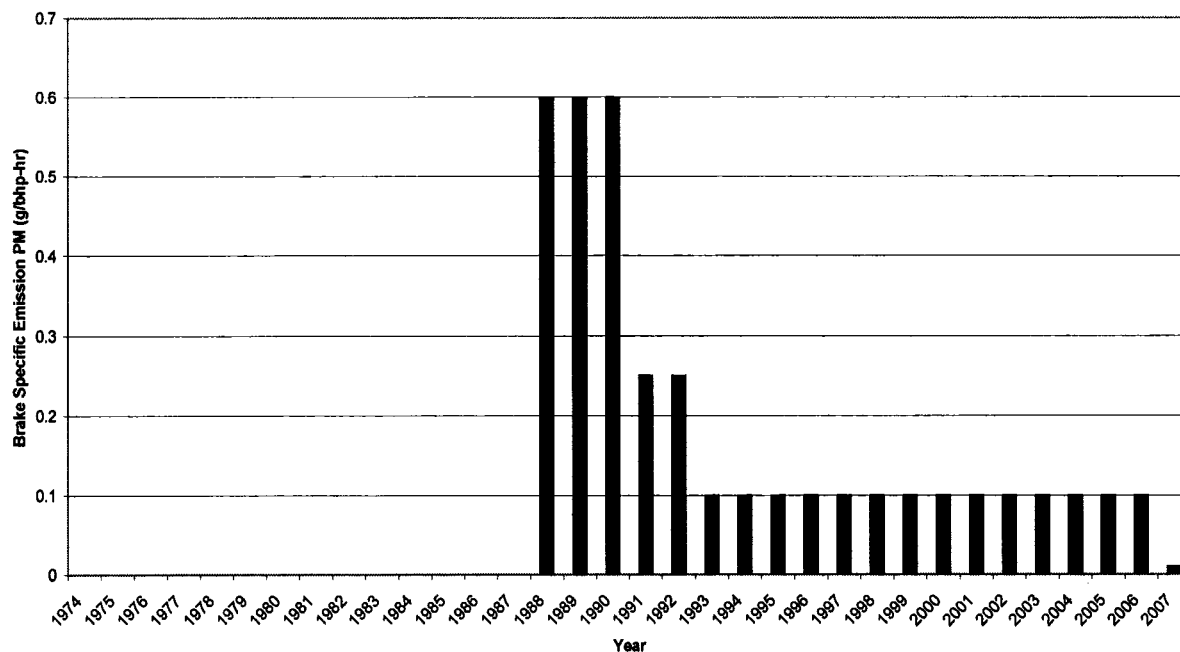


Figure 2: US EPA Emissions Standards Timeline for HDDV's for PM

Table 2: EPA Emission Standard History for HDDV's

Year	CO (g/bhp-hr)	NO _x (g/bhp-hr)	HC (g/bhp-hr)	PM (g/bhp-hr)
1974	40	16		-
1979	25	5		-
1984	15.5	10.7	1.3	-
1988	15.5	6.0	1.3	.60
1990	15.5	6.0	1.3	.60
1991	15.5	5.0	1.3	.25
1993	15.5	5.0	1.3	.10
1998	15.5	4.0	1.3	.10
2004	15.5	2.5		.10
2007	15.5	.20	.14	.01

1.4.3. Units of Measure for Emissions

Prior to presenting the results of this thesis research, a few comments are provided on the units of measure that are typically used for reporting emissions measurements.

Results from emissions testing can be manipulated in several different ways based on how the emission units are reported. For example, the current EPA regulations specify heavy-duty diesel emission limits in terms of brake-specific emissions, with units of grams per brake horse power-hour (g/ bhp-hr) or equivalently in metric units of grams per kilowatt-hr (g/kW-hr). Total vehicle emissions in g/hr scales proportionally to engine size (hp). The g/bhp-hr emission unit allows for comparison between emissions from non-road sources (lawn mower, boat, etc.) to a class 8 truck. Other emissions units commonly used in prior research are g/mile and g/hour. For the purpose of this research, results will be reported in g/bhp-hr and g/mile for mobile testing or g/hr for school bus idling where the miles are always zero.

Brake specific emissions (g/bhp-hr) are the mass flow rate of the pollutant per unit power output. Time-specific emissions, or grams of pollutant per unit time, are required to compute these measurements (calculations are shown in Chapter 2). Emissions from an internal combustion engine are commonly measured as a concentration (corresponds to the mole fraction multiplied by 10^6 or the percent multiplied by 10^2 , respectively) from a dilution tunnel in ppm or percent by volume.¹⁸ Concentration is converted to mass using a mass balance on the gas being emitted from the exhaust pipe. Procedures for performing this calculation are given in the Code of Federal Regulations (CFR) by multiplying the mole fraction of the pollutant by the mixing volume measured in the dilution tunnel (device where the engine exhaust and dilution air are mixed together) and multiplying by the density of the pollutant and subtracting the background emissions measured during the test.¹⁹ The work from the vehicle is obtained from the engine torque and is further discussed in Chapter 2.

1.4.4. Emissions Testing

Emissions are tested by applying a known load to an engine or vehicle and by sampling the engine exhaust. Loads can be applied to an engine in a variety of ways, such as a dynamometer system or by mobile in-use testing of the engine installed in a vehicle. A dynamometer system is used to measure the mechanical power an engine can produce against known loads. There are two categories of dynamometers: engine and chassis. Each of these types of emissions testing is described in the following section. The majority of testing in the present study was performed using mobile testing; however the past practice required by EPA was to certify a new engine on an engine dynamometer.

1.4.4.1. Engine Dynamometer Emissions Testing

An engine dynamometer is a dynamometer test system that is used to simulate road conditions and loads in stationary settings to gather data about the engine's performance under those conditions. With an engine dynamometer the engine is installed on a test system, which is more convenient to work with and has greater accuracy than if the engine were installed in a vehicle. In the engine dynamometer system, the engine is supposed to simulate performance characteristics as if the engine were actually being used in the vehicle. Power is usually measured at the flywheel (mounted at the rear of the crankshaft and used to store up rotational energy during the power impulses of the engine²⁰) of the engine when using an engine dynamometer, which is difficult when using a chassis dynamometer or mobile testing. As described in the following sections, measuring the power at the flywheel gives the actual power produced by the engine however, because it results in no transmission or driveline losses to influence the results.

An engine dynamometer is typically operated with a specific software package provided by a vendor. A typical engine dynamometer test system is shown in Figure 3.

A disadvantage for the EPA inspectors when using an engine dynamometer is the need for the missing vehicle subsystems required for engine operation. Such subsystems including: fuel supply, electrical supply, exhaust extraction, air flow for cooling and for combustion air, coolant temperature control, and throttle actuation are required to maintain control over the engine.

Testing for emissions with an engine dynamometer significantly lacks some real conditions that influence emission results from a vehicle. The lack of real conditions on the engine dynamometer provides the engine manufacturer an opportunity to manipulate engine emissions. Emission influencing factors such as temperature and humidity, wind resistance, frictions from the tires and road, driveline losses, real vehicle accelerations and decelerations, etc. are almost impossible to simulate with an engine dynamometer. Installing emission reduction after treatment devices such as particulate filters is possible with an engine dynamometer, but installation of these devices when the engine is in the vehicle is more practical for emission testing. The engine dynamometer is currently used however, for HDDV emission certification in the United States.

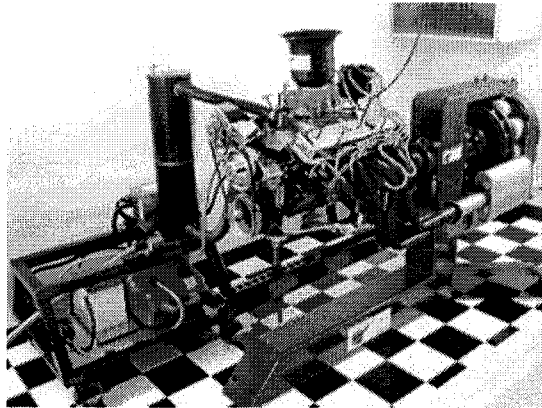


Figure 3: Engine dynamometer in-use²¹

1.4.4.2. Chassis Dynamometer Emissions Testing

A chassis dynamometer is a machine that can be used to simulate road conditions and test a vehicle's performance without actually putting the vehicle on the road. The chassis dynamometer system uses a series of rollers driven by the wheels of the vehicle. The rollers are connected to a power absorber system capable of controlling the load applied to the rollers. There are three primary types of chassis dynamometers, each characterized by the technology employed to absorb power: water brake, eddy current, and electric motor. Chassis dynamometers can be used for diagnostic purposes, as well as performing emissions and fuel mileage testing.

A variety of emissions test cycles have been created with the purpose of performing emissions testing on a chassis dynamometer. These test cycles make it possible to simulate road conditions, which are further explained in Chapter 3. These cycles are used in conjunction with the dynamometer to perform emissions certification and testing. Certain types of dynamometers work better for each of these applications discussed. Chassis dynamometers have their advantages over engine dynamometers because no modification has to be done on the vehicle prior to testing (e.g. engine removal). Some

disadvantages associated with using a chassis dynamometer include the inability to achieve repeatable measurements due to such factors as driveline losses or tire wear, pressure and temperature. Another disadvantage to the chassis dynamometer is that, although it includes some parameters that are not present in engine dynamometer testing such as driveline losses and wheel friction, it still lacks the real conditions (changing temperature and humidity, wind resistance, road conditions, etc.) mobile testing can provide.

In order for a dynamometer to simulate road conditions, it must have a means of applying load to the rollers, which the wheels of the vehicle ride on. The water brake is one type of braking system that is used for this purpose. The water brake produces a load by pumping water. The pump is driven from the rollers, which the tires of the vehicle being tested ride on. The characteristics of the pump can be changed to apply varying degrees of load to the rollers. The advantages of a water brake are that the system is easy to maintain and relatively inexpensive. The water brake dynamometer can also be operated for extended periods of time because the system is actively cooled.²² The disadvantage of a water brake is that it cannot apply a load at zero RPM and is slow to respond to quick changes in load conditions. Another disadvantage is that it requires a significant amount of hardware installed on the premises in addition to the dynamometer itself. Since the water brake dynamometer uses a water pump to apply load, it requires an ample water supply and drainage to remove the used water. In many cases a cooling tower is needed to lower the temperature of the exhaust water before it is returned to the environment. The water brake dynamometer is intended for applications that require the dynamometer to be run for extended periods of time and have facilities that can

accommodate the amount of hardware necessary for this type of dynamometer to be operated.²³ Water brake dynamometers are typically installed in-ground, but some companies have developed a more expensive above ground ramp system.

As part of the research study presented in this thesis, a variety of chassis dynamometers were evaluated for potential use in school bus emissions testing. For example, the research team visited and operated the water brake system shown in Figure 4 at the Johnson Towers Truck Service Company in Mt. Laurel.

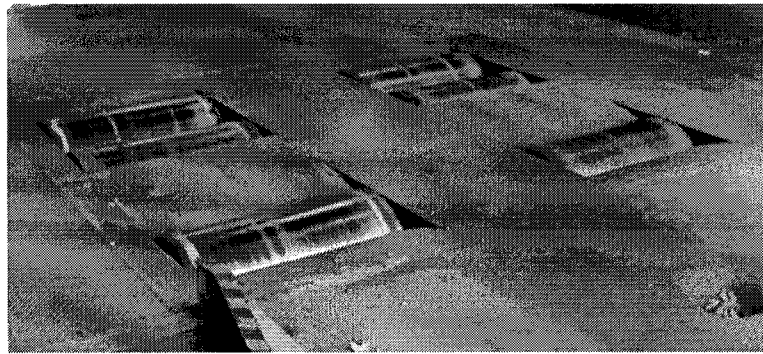


Figure 4: Water brake dynamometer installed in ground

The eddy current brake is another means of applying load to the rollers of the dynamometer. The eddy current brake applies load by creating a magnetic field, which applies a force to a shaft that is connected to the rollers. The eddy current dynamometer has many advantages; one being that the load is applied with a magnetic field so it is frictionless. Compared to the water brake system, the physical size of the dynamometer is much smaller, and requires much less hardware installed to operate the system. The eddy current dynamometer can easily be mounted either above ground or in a pit and is also relatively inexpensive. There are also some disadvantages of the eddy current. Since the eddy current is air cooled, there is a limit on how long it can be operated. It is primarily designed for shorter tests, but can be used for some longer tests.²⁴

The third type of system used to apply load for a chassis dynamometer is the electric motor brake or AC dynamometer. The electric motor applies a load via direct coupling with the rollers on the dynamometer. The motor can then apply a load to the rollers by providing a resistive force on the axle of the rollers. The electric motor dynamometer is capable of running almost any test that has been created. It can apply a load to the rollers at zero RPM, which none of the other brake systems are capable of. The primary disadvantage of the electric motor dynamometer is that it is very expensive; almost eight times that of the water brake and over ten times that of the eddy current.²⁵ Electric motor dynamometers can perform complicated real-world driving cycles that the other chassis dynamometers cannot, however the electric motor dynamometers are so expensive that there are only two in the US.

1.4.4.3. Mobile In-Use Emissions Testing

The third and final type of emissions testing is mobile or in-use testing. A mobile emissions test includes an engine installed in the test vehicle while on the road running a prescribed test cycle. Mobile testing allows the school buses to be tested under conditions that cannot be reproduced on any dynamometer, or within an environmental chamber, but do allow for repeatable driving routes to be run.

Mobile testing was chosen as the research method for this project for several reasons. The main reason was that the EPA plans to switch to mobile testing by 2010 for all of their emissions testing.²⁶ Mobile testing provides a more accurate and realistic account of emissions actually from a vehicle while it is in-use, something an engine or chassis dynamometer system in a lab will never be able to reproduce. Another reason why mobile testing was chosen is due to the ease of installing emissions measuring equipment

and emissions reduction devices. There were no modifications necessary prior to vehicle testing, the engine did not have to be removed, and the expense of a test system (engine or chassis dynamometer) was not needed. Mobile emissions measurement equipment is advanced enough to provide similar controls to those which were previously only available for dynamometer testing, such as vehicle interface and driver assist routing aid, which will be discussed later.

Previous research in the emissions field was done without the advantage of a test track for mobile testing often forcing the researchers to work in the lab on an engine or chassis dynamometer test system. At ATC there are several test track options for running test cycles uninterrupted from outside influences, such as traffic and pedestrians.

Another important factor when choosing mobile testing was the fact that engine manufacturers actually misrepresented emissions levels when testing their engines on engine dynamometers. In 1998 the Department of Justice and the Environmental Protection Agency found seven diesel engine manufacturers guilty of installing software that disables pollution prevention control devices after completing EPA standard tests. These companies are Caterpillar, Inc., Cummins Engine Company, Detroit Diesel Corporation, Mack Trucks, Inc., Navistar International Transportation Corporation, Renault, and Volvo Truck Corporation. Combined, these manufactures were ordered to pay fines totaling \$83.4 million, which is the largest civil penalty ever for violation of environmental law.²⁷ This penalty was also the third in a series actions brought against engine companies that allow their ECM's to "selectively" prevent pollution. The first exposure of the defeat device came in 1995 when the EPA and the Department of Justice found GM guilty and penalized them \$45 million. The American Honda Motor Co. was

penalized \$267 million and the Ford Motor Co. for \$7.8 million to conduct environmental projects.²⁸ Mobile testing eliminates any cheating by the engine manufacturers, since the emissions being measured by the analyzer are after the certification tests and the manufacturer does not have the ability to change the ECM programming.

A disadvantage to mobile testing is that the weather cannot be controlled (snow, rain, heavy winds, etc.). Some emissions, particularly NO_x, have been shown to be a strong function of ambient conditions. Though these are real conditions HDDV's may undergo, it makes for a difficult time for researchers and the vehicle's driver (trying to follow a prescribed drive cycle) when testing for mobile emissions. Indeed, the human error associated with the driver is another disadvantage of mobile testing. Though mobile testing does not result in the wear and tear of chassis dynamometer on the vehicle, the driver cycle repeatability is inferior to what can be accomplished on the chassis dynamometer.

1.5. Diesel Emission Reduction Strategies

Several different emissions reduction technologies will be tested with mobile testing over the course of the school bus emissions testing project. The technologies that are going to be tested are the Johnson-Matthey CRT Particulate Trap, Engelhard DPX Particulate Trap, PFC crank case breather, the PFC flux wave cell, and other various technologies. Alternative fuels to be tested include #2 diesel, ultra-low sulfur diesel (ULSD), biodiesel/# 2 diesel blends, and biodiesel/ULSD blends. The results from the alternative fuel-testing portion of the project are presented in this research.

In an attempt to meet the stringent 2007 EPA emissions standards, all HDDV engines will need an emission reduction technology. In the past 30 years of EPA emission

regulation engine manufacturers were able to meet the new standards by only changing their engine designs (e.g. fuel injection systems, exhaust gas recirculation, and electronically controlled engines). The most common types of emission reduction strategies are after treatment devices (e.g. particulate traps) and alternative fuels. Fuel additives and other reduction devices (e.g. Selective Catalytic Reduction, Diesel Oxidization Catalysts, etc.) are also used, but are not as common and widely available as particulate traps and some alternative fuels. In order to meet the new standards for HDDV's the emission reduction technologies needed will be costly and usually come with a fuel penalty. The research presented in this thesis will focus primarily on the emissions reduction benefits from various alternative fuels. A follow on study is currently underway that will focus on after treatment devices.

1.5.1. Alternative Fuels

An alternative fuel is defined as a fuel other than petroleum diesel or gasoline.²⁹ The purpose of an alternative fuel is to have a cleaner burn and produce lower emissions. Alternative fuels will also reduce our reliance on imported oil. The most common alternative fuels such as biodiesel and ultra low sulfur diesel (ULSD) have been shown to reduce some diesel emissions significantly in cars and trucks. For this research, # 2 conventional petroleum diesel (low sulfur ~360 ppm), B20 (20% by volume biodiesel, 80% by volume #2 conventional petroleum (~360 ppm) diesel), ultra low sulfur diesel (~15 ppm), and a biodiesel-ultra low sulfur diesel (20% by volume biodiesel, 80% by volume ultra low sulfur diesel (~15 ppm)) mixture were examined.

Biodiesel is an alternative fuel that is a cleaner-burning diesel replacement to # 2 diesel. Biodiesel is made from natural renewable sources such as new and used vegetable

oils and animal fats. The most common source of biodiesel in the US is soybeans. Biodiesel can be used pure or in different blends with #2 conventional petroleum diesel. These blends are classified by percent volume of biodiesel. For example, a blend of 20 percent biodiesel and 80 percent conventional petroleum diesel is called B20. Research has shown that the best emission reductions for PM, HC, and CO come from higher percent biodiesel blends and pure biodiesel, B100.³⁵ One large obstacle in the widespread use of biodiesel as a permanent petroleum diesel replacement is availability. Biodiesel resources are estimated at about two billion gallons per year, which is considerably lower than the 60 billion gallons used annually by the USA distillate market.³⁰

One tradeoff when using pure biodiesel, B100, is that it can significantly increase NO_x depending on the duty cycle.³¹ The NO_x increases when using biodiesel could be caused by the higher fuel density and lower heating value of the fuel.³² Increasing oxygen content in the fuel has caused significant increases in NO_x in previous research.³² The NO_x tradeoff is not a large concern, due to the low sulfur content of biodiesel (~24 ppm), which will work with NO_x reducing technologies that require low sulfur fuel. Biodiesel blends higher than B20 however, can cause problems with deterioration of existing gaskets and could cause gelling in the winter. A basic mixing process called splash blending creates a mixture of biodiesel and conventional petroleum diesel. Biodiesel has a higher specific gravity (~. 88) than conventional petroleum diesel (~. 85), so splash blending should involve mixing the biodiesel on top of the conventional petroleum diesel.

Biodiesel has other advantages besides decreasing HC, PM, and CO emissions. Every unit of energy needed to produce biodiesel results in 3.24 units of fuel energy,

while producing conventional petroleum diesel requires more energy to produce the fuel than is generated.³³ As far as safety factors are concerned biodiesel has a higher flashpoint than conventional petroleum diesel and is biodegradable and non-toxic. Also, since biodiesel is renewable, CO₂ reductions are indirectly created from the lifecycle of biodiesel. Biodiesel also has no known blending problems when being mixed with ULSD. Biodiesel also improves lubricity of the engine, where ULSD does not, and a combination of biodiesel and ULSD would offset the loss of lubricity when using just ULSD. ULSD and biodiesel both have higher cloud points than conventional petroleum diesel, which could be a problem with gelling in colder weather conditions. The cloud point of a clear distillate fuel is the temperature at which the fuel becomes hazy or cloudy because of the appearance of wax crystals.³⁴

In a comprehensive review compiling several separate biodiesel studies, the EPA concluded that common blends of B20 reduced HC emissions by 20 %, PM emissions by 10 %, and CO emissions by 11 %.³⁵ NO_x emissions increased slightly in some engines (~2%) and CO₂ emissions showed little or no difference. Some school districts such as Medford Township in NJ are already using B20 in half of their 44 buses³⁶. As part of the present study, tests were performed on some of the buses in the Medford conventional and biodiesel fueled fleet. The results from those tests are presented in Chapter 4.

Ultra low sulfur diesel (ULSD) is an alternative fuel made to have less than 15-ppm sulfur. ULSD will be the only diesel fuel allowed in the U.S. after 2006. PM emissions have been shown to decrease slightly with the use of ULSD, however the real advantage of the fuel comes when combining it with an emission after treatment technology. Since sulfur has been known to poison catalysts it is required that ULSD be used for most

particulate traps and catalytic converters. When combining ULSD with these technologies significant reductions in some emissions have been reported.

The USEPA classifies ULSD as having no more than 15-ppm sulfur content, with the current U.S. regulations allowing up to 500-ppm sulfur for diesel fuel used for highway transportation. Previous studies show that ULSD by itself reduces HC emissions by 13 %, PM emissions by 13 %, CO emissions by 6 %, and NO_x emissions by 3 %. With the addition of a particulate filter, ULSD can reduce HC and CO emissions by 90 %, PM emissions by 80%, and NO_x emissions by 15 % to 20 %.³³ Compared to conventional petroleum diesel, a B20 biodiesel blend costs an additional \$0.12 to \$0.20 and ULSD costs an additional \$.05 to \$0.15.³³

1.5.2. Particulate Traps

Although exhaust after treatment tests have yet to be completed, a review of the current status of available devices was conducted as part of the present research study. A brief review is presented here. A diesel particulate filter or trap physically captures particulates from the exhaust and prevents them from entering the atmosphere. The Johnson Matthey Continuously Regenerating Technology (CRT) Particulate Filter and the Engelhard DPX Catalyzed Diesel Particulate Filter are the only two diesel particulate traps approved by the EPA for HDDV's as part of their verified after treatment technology list³⁷. A diesel particulate filter incorporates a filtering device to trap liquid and solid particulates. Materials used to construct diesel particulate filter include ceramic monoliths, wire mesh, woven silica fiber coils, ceramic foam, etc. A catalyst is used to promote combustion of the carbon inside the filter, producing carbon dioxide.

The three types of particulate filters are “catalytic, “fuel-borne catalyst,” and

“continuously regenerating” particulate filters. In a catalytic filter, the catalyst is applied directly to the filter material. In a fuel-borne catalyst filter, the catalyst is added directly to fuel. A continuously regenerating filter uses a catalyst in front of the monolith to oxidize NO to NO₂, which absorbs the particulate matter and causes combustion in the second catalyst chamber. The combustion of the particulates is the “cleansing” or regeneration step of the process. A design schematic of a typical diesel particulate filter is shown in Figure 5. Similar to other exhaust after treatment technologies, the reduction capabilities of this technology depend on the amount of sulfur in the diesel or alternative fuel used and the exhaust temperature. Studies show that most diesel particulate filters can achieve from 90 to 99% reduction of particulate matter, hydrocarbons, and carbon monoxide.³⁸ However, particulate traps have shown only slight reduction of NO_x. Diesel particulate filters are not available for all families of engines. However HDDV’s newer than 1994 that are electronically controlled will generally meet the retrofit guidelines provided by the filter manufacturers.

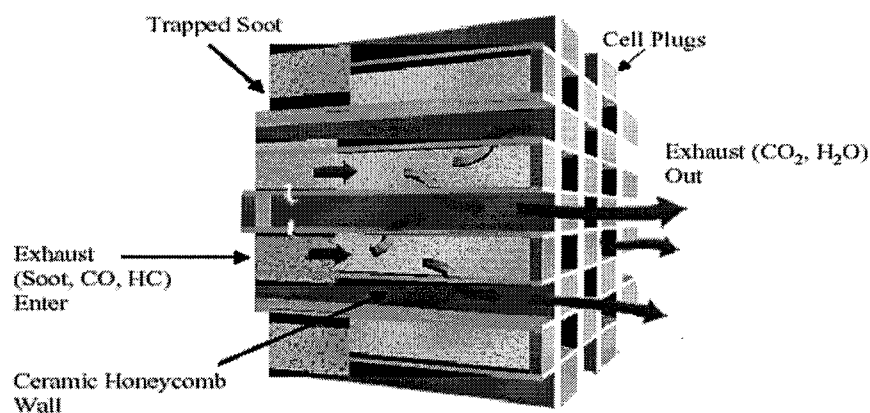


Figure 5: Schematic of a diesel particulate filter³⁹

In order for an effective regeneration to occur, the exhaust temperature must reach a

temperature between 350-400 °C. If this exhaust temperature is not reached, the soot collected in the filter is not combusted and the particulate trap becomes clogged. Another disadvantage when using a particulate filter on an HDDV is the effect of sulfur in the fuel. Sulfur inhibits the active sites on the catalyst, which results in a less active catalyst and a higher exhaust temperature requirement for regeneration. The oxidation of SO₂ to SO₃ over the platinum oxidation catalyst takes place in preference to the oxidation of NO to NO₂⁴⁰. Therefore, the NO oxidation reaction is inhibited, and the NO₂ is less available to burn off the trapped soot.

Johnson Matthey's EPA approved particulate filter provides its diesel particulate retrofit in the form of a continuously regenerating technology (CRT), which is a trade name for a catalytic, two-stage, passive particulate filter system. The CRT system (shown in Figure 6) regenerates at temperatures below 300 °C, using ultra low sulfur diesel fuel. Johnson Matthey has recently patented this principle of using nitrogen dioxide to oxidize diesel particulate matter.

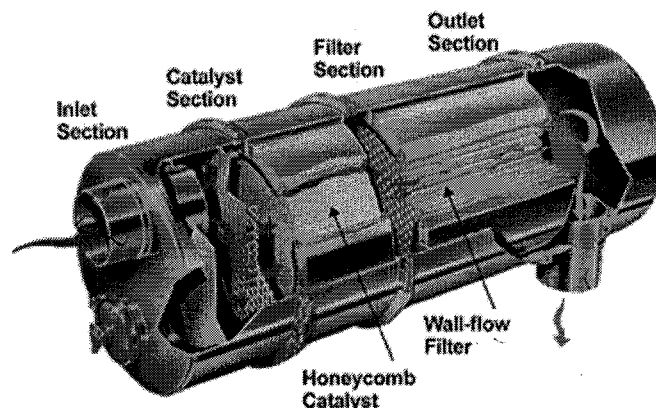


Figure 6: Johnson Matthey CRT diesel particulate filter

The CRT diesel particulate filter system consists of two separate chambers. The first chamber is a ceramic monolith, coated with the platinum catalyst. In the ceramic monolith chamber, carbon monoxide and hydrocarbons are combusted to form carbon

dioxide and water. The first stage also increases the proportion of nitrogen dioxide to nitrogen oxide. In the second chamber the exhaust passes through another monolith, which forces the exhaust through the pores. The remaining soot is trapped and burned off by the nitrogen dioxide from the first stage.⁴¹ Restrictions do exist for this technology however, such as the exhaust gas temperature, the NO_x to PM ratio, and sulfur content in the diesel fuel. The restrictions are as follows: the exhaust gas temperature for the CRT must be at least 275 °C, the sulfur content in the fuel must not exceed 50 ppm (ULSD has a sulfur content of less than 15 ppm), and the exhaust NO_x to PM ratio must be between 8:1 and 25:1 by weight. The minimum exhaust temperature has been determined by studies such as the California Air Resources Board for post-1994 engine retrofits, and the Diesel Emission Control - Sulfur Effects (DECSE) study on a CAT 3126 engine. The high exhaust temperature is required for the filter regeneration to take place, which according to California ARB must have a temperature of 270 °C for 40% of the operating time of the filter. According to the DECSE report, the filter has shown to regenerate as low as 300°C, provided that ultra low sulfur diesel fuel (15ppm) was used. ULSD must be used with the CRT because the sulfur deteriorates regeneration.⁴² Sulfur is an inhibitor, which strongly competes with NO_x in the exhaust. Thus, the active sites in the catalyst become blocked by a competitive adsorption between sulfur dioxide and nitrogen oxide. The result is a lower NO₂ generation, and in order to obtain generation, the exhaust temperature must be raised.⁴³

Engelhard's EPA approved particulate filter provides its diesel particulate retrofit in the form of a DPX catalyzed particulate filter. The DPX filter is a platinum and base metal oxide catalyst-coated ceramic wall-flow filter. The catalyst coating is embedded

into the porous filter walls and oxidized the collected particulate matter, hydrocarbons, and carbon monoxide from the exhaust.⁴⁴

According to Engelhard Corporation the DPX filter delivers 70-98% PM reduction and 70-98% carbon monoxide and hydrocarbon reductions.⁴⁵ The DPX particulate filter is effective when used with sulfur fuel ranging from 5 PPM to 500 PPM, and no fuel additives are required. Under such circumstances, oxidation catalyst technology in the form of a muffler replacement would be more suitable and would deliver 25-50% PM reduction, 50-80% hydrocarbon reduction, and 40-90% carbon monoxide reduction. Engelhard Corporation also claims that the DPX Soot Filter requires an exhaust gas temperature of 375°C for at least 25% of the time.⁴⁶

1.6. Thesis Organization

This thesis presents the results of an experimental study aimed at evaluating emission reduction strategies for diesel powered school buses in New Jersey. Chapter 2 details the experimental procedure used to acquire and analyze emissions data from the school buses. The specifics of the emission measurement equipment, the testing location, the test vehicles, and the data management are discussed in this chapter. Chapter 3 details the development of a new mobile emissions test cycle for school buses. The test cycle was developed using actual school bus route GPS data from distinct routes in NJ school systems.

Chapter 4 describes preliminary testing of school buses in Medford, NJ. The Medford School District is the first in the state of New Jersey to operate a majority of its fleet on biodiesel. Testing was conducted solely by Rowan University on four Medford school buses in an attempt to acquire as much emission data as possible. Chapter 5 details

the experimental testing conducted in the Aberdeen Testing Center environmentally controlled chamber. The goal of the chamber testing was to evaluate the effects of varying temperatures and humidity on an idling school bus. From the data, a correction factor was developed for the buses to account for varying temperature and humidity as encountered during mobile testing. School bus idling emissions data was also acquired that could lead to further recommendations for the New Jersey SIP.

Chapter 6 details the experimental testing of alternative fuels in school buses conducted on the Aberdeen Testing Center mobile testing track. Three school buses were tested with three alternative fuel types and #2 conventional petroleum diesel to evaluate the emission effects of alternative fuels on different engines. The school bus tests were performed using the mobile test cycle created in Chapter 3. The NO_x emissions data collected was corrected for temperature and humidity using the correction factor developed in Chapter 5. The biodiesel results from this ATC mobile test were compared to the results previously obtained at the Medford Township School District with buses that have been running on biodiesel for five years, as shown in Chapter 4. Chapter 7 provides conclusions and suggestions for future work on both emission reduction technologies for school buses and mobile school bus testing cycles.

2. Experimental Procedure and Equipment

2.1. Introduction

The purpose of this chapter is to describe the test vehicles, the test facilities, and the equipment used to measure emissions for mobile and idle school bus testing. This chapter will also provide information on how data collected from various instruments was compiled and managed.

2.2. Rationale for School Bus Selection

An early challenge for the project was to choose three diesel engines typically found in school buses across New Jersey for diesel emissions testing. Among the criteria considered for the selection was availability of the buses, frequency of use of a particular bus type in New Jersey, and popularity of engine type with respect to previous school bus emission studies. Another important factor in bus selection was the age of the school bus. Since school buses are replaced from a school districts fleet every 13 years, it was important to stay in the scope of the project and chose a bus that would still be in service for a significant time after completion of this study.

2.2.1. School Bus Types in NJ

One criteria for the selection of the school buses was developed after determining the types of buses that are commonly used in New Jersey school systems. NJDOT provided a comprehensive study of the engines used in school buses across the entire state. As shown in Table 3, specific engine types were used in the study done by Polk Automotive Intelligence of Detroit to organize buses from all NJ school districts. The three buses that were ultimately chosen for emissions testing are shown in bold in Table 3. In addition to the survey compiled by NJDOT, a survey was taken by Rowan University students in the

townships of Washington, Middletown, Medford, and Glassboro to see which buses they were using. Medford, and Washington townships both use International engines in their buses (T-444E and DT466), while Glassboro use Caterpillar engines in their buses. Middletown also uses Caterpillar and International, along with GMC, Detroit Diesel, and Cummins.

Table 3: Engine types used in NJ School Districts⁴⁷

Engine Manufacturer	Engine Model	Total Number of buses in New Jersey
Caterpillar	3116	581
Caterpillar	3126	1356
Caterpillar	3406	1
Caterpillar	3208	13
International	T-444E	2232
International	DTA 466	15
International	DTA 360	891
International	DT 466	1113
International	DT 408	151
International	DT 360	258
International	7.3 L	1184
Detroit Diesel	8.2 L	126
Ford	7.8 L	20
Ford	6.6 L	99
Cummins	5.9L B series	1816
General Motors	7.0 L	9
General Motors	7.4 L	84
General Motors	6.0 L	494
General Motors	5.7 L	2
General Motors	8.1 L	19
Unknown	Unknown	409
Total Buses in NJ	-	10873

Previous school bus emissions studies were reviewed to help aid in the school bus

selection to see what types of engines were commonly being tested. An SAE study in 1999, used a Navistar International T-444E engine to study the effects of alternative fuels on emission levels.⁴⁸ The T-444E was also used in another steady state comparison test of biodiesel and conventional petroleum diesel by FEV Engine Technology, Inc.⁴⁹ Further biodiesel testing was done on two Cummins B Series engines, which were fueled with 100% biodiesel for a 48 month period by the Agricultural Engineering Department at the University of Missouri-Columbia.⁵⁰ Also, as mentioned in the previous chapter, beginning in early 1998, the Medford (New Jersey) Township Public Schools voluntarily started a 4-year demonstration program for B20 (20% biodiesel made from soybeans, 80% conventional petroleum diesel). In its fleet of 44 buses, 22 are operated on B20; the rest are operated on conventional petroleum diesel. Medford used International DTA360 and DT-466E for the testing of the biodiesel fueled buses.

Another factor in selecting a bus engine for testing was availability for purchasing. Though the Caterpillar 3126 was the third highest most commonly used bus type in NJ, there were no buses equipped with this engine available for purchase within the constraints of this study. The final selection of the three buses upon reviewing the specifications for selection was an International T-444E and DT-466E along with the Cummins B Series engine. School bus engine specifications for the three engines selected are shown in Table 4.

Table 4: Engine selection for school bus emissions testing

Engine	Year	Chassis/Body	Engine Hp	Rated Speed	Miles
T-444E	1997	98' International	190	2300	73,471
T466	1997	98' International	190	2300	47,862
5.9L Cummins	1996	97' Ford	190	2200	85,516

2.2.2. Engine Specifications

2.2.2.1. 1997 International T-444E

The International T-444E is a four cycle, 8-cylinder (V-8) diesel engine and is commonly used in truck and bus Vehicle Classes 2 through 8 trucks and buses. This engine is available at 175-230 hp and has a 7.3 L displacement (the engine tested is rated at 190 hp). The T-444E idles at approximately 700 rpm, which is not adjustable for this engine. The DT-466E engine lug curve is shown in Figure 10. The combustion system for the engine is direct injection and it is turbocharged with a wastegate (a valve that allows the exhaust to bypass the turbine blades). The wastegate senses the boost pressure allowing some exhaust to bypasses around the turbine blades if the pressure gets too high.⁵¹ The T-444E engine is air-to-air intercooled and has a 17.5:1 compression ratio. Among its many features include an electronic control module (ECM), electronic glow plugs, and an electro-hydraulic fuel system or HEUI (hydraulically actuated, electronically controlled unit injectors). The T-444E used by Rowan University for emissions testing is shown in Figure 7.

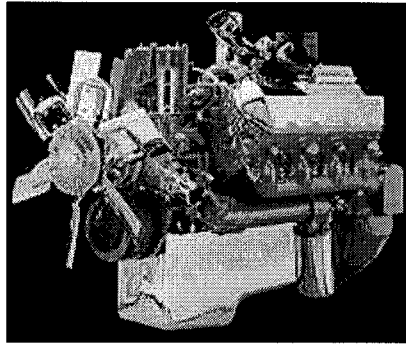


Figure 7: International T-444E diesel engine

2.2.2.2. 1997 International DT-466E

The DT466 is a four cycle, in-line 6-cylinder diesel engine. This engine is available at 195-230 hp and has a 7.6 L displacement (the engine tested is rated at 190 hp). The combustion system for the engine is direct injection and it is turbocharged with a wastegate. The DT-466E idles at approximately 700 rpm, which is not adjustable for this engine. The DT-466E engine lug curve is shown in Figure 11. The engine is air-to-air intercooled and has a 16.4:1 compression ratio. Among the engines many features include an ECM and an electro-hydraulic fuel system. The DT-466E used by Rowan University for emissions testing is shown in Figure 8.

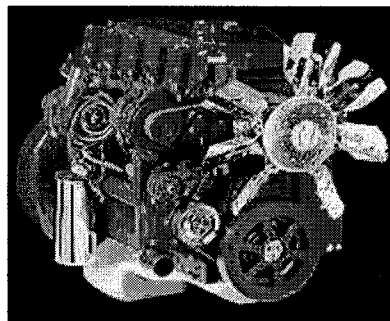


Figure 8: International DT-466E diesel engine

2.2.2.3. 1996 Ford Cummins 5.9 L ISB Series

The ISB engine is a four cycle, 6-cylinder diesel engine. This engine is available at a range of about 185-300 hp with a 5.9 L (the engine tested is rated at 190 hp). The combustion system for this engine is direct injection and is turbocharged a wastegate. The B series idles at approximately 800 rpm, which is not adjustable for this engine. The Cummins 5.9 L B Series engine lug curve is shown in Figure 12. The ISB engine is air-to-air intercooled and has a 16.5:1 compression ratio. The 96' Cummins B Series is not equipped with an ECM. The Cummins 5.9 L B Series engine used by Rowan University for emissions testing is shown in Figure 9.

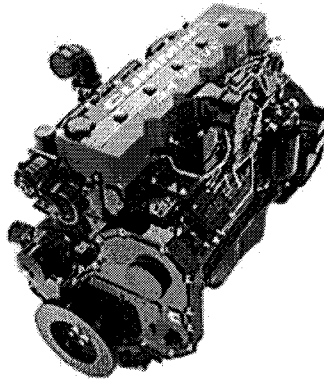


Figure 9: Cummins 5.9 L B Series diesel engine⁵²

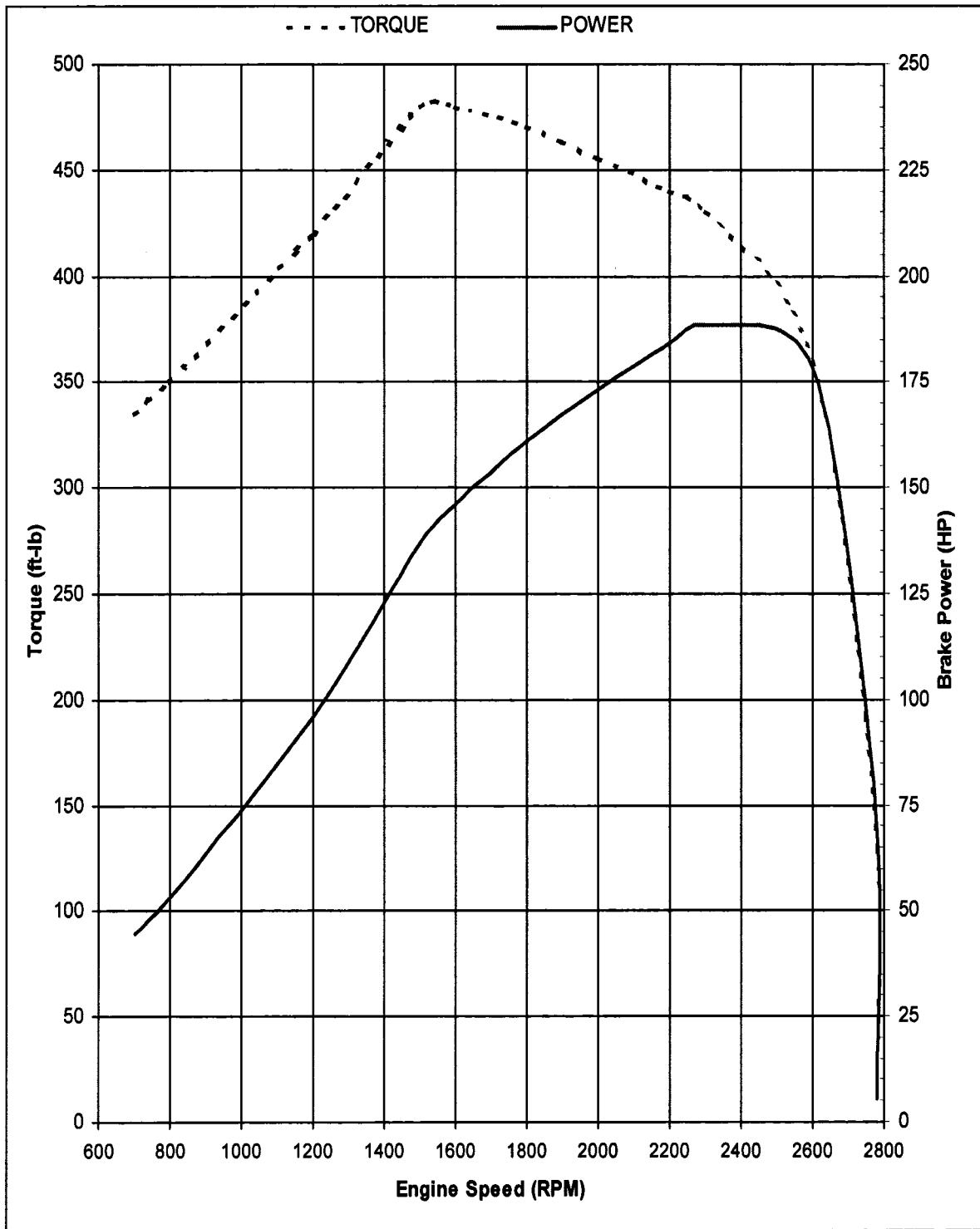


Figure 10: T-444E engine lug curve

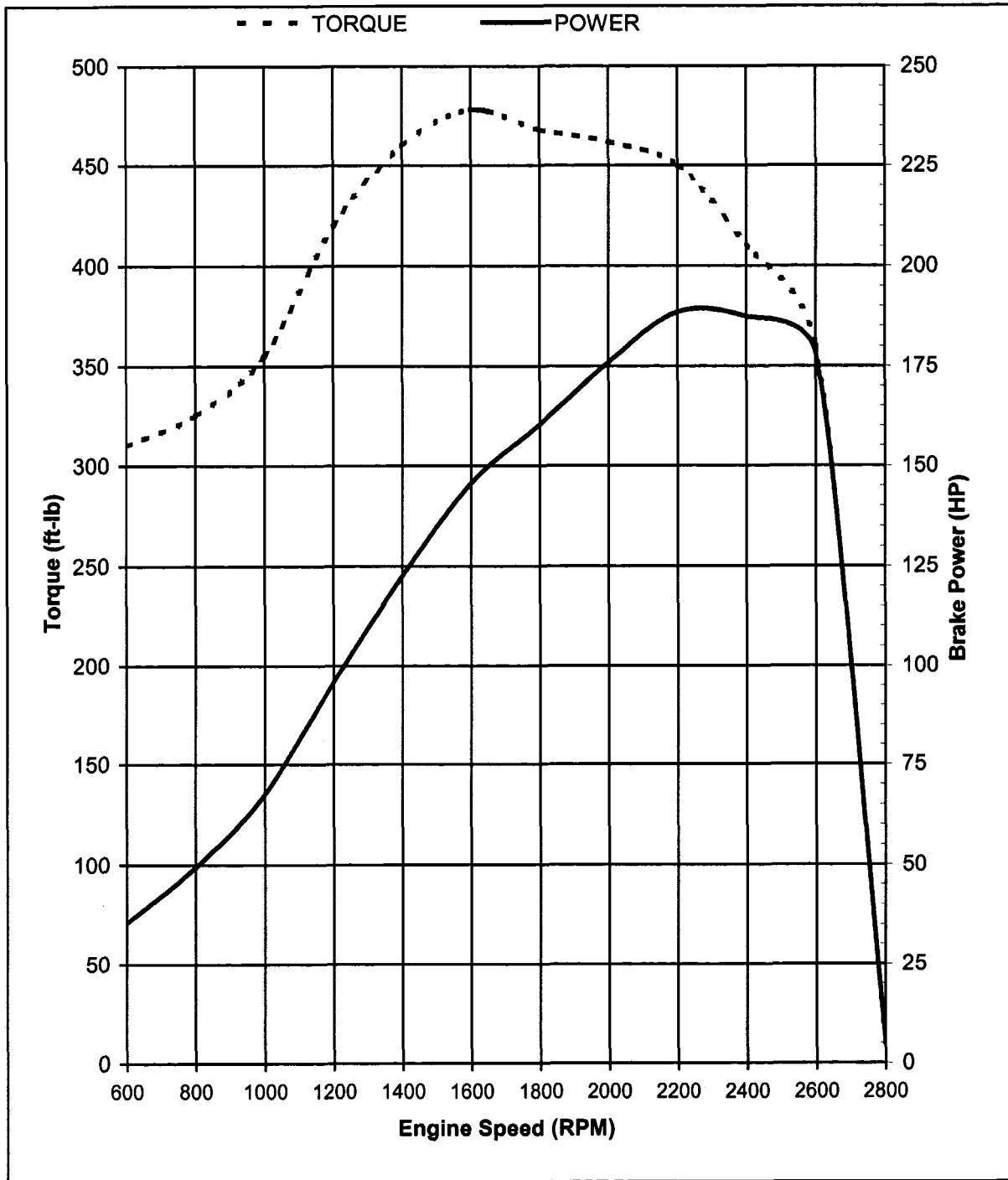


Figure 11: DT-466E engine lug curve

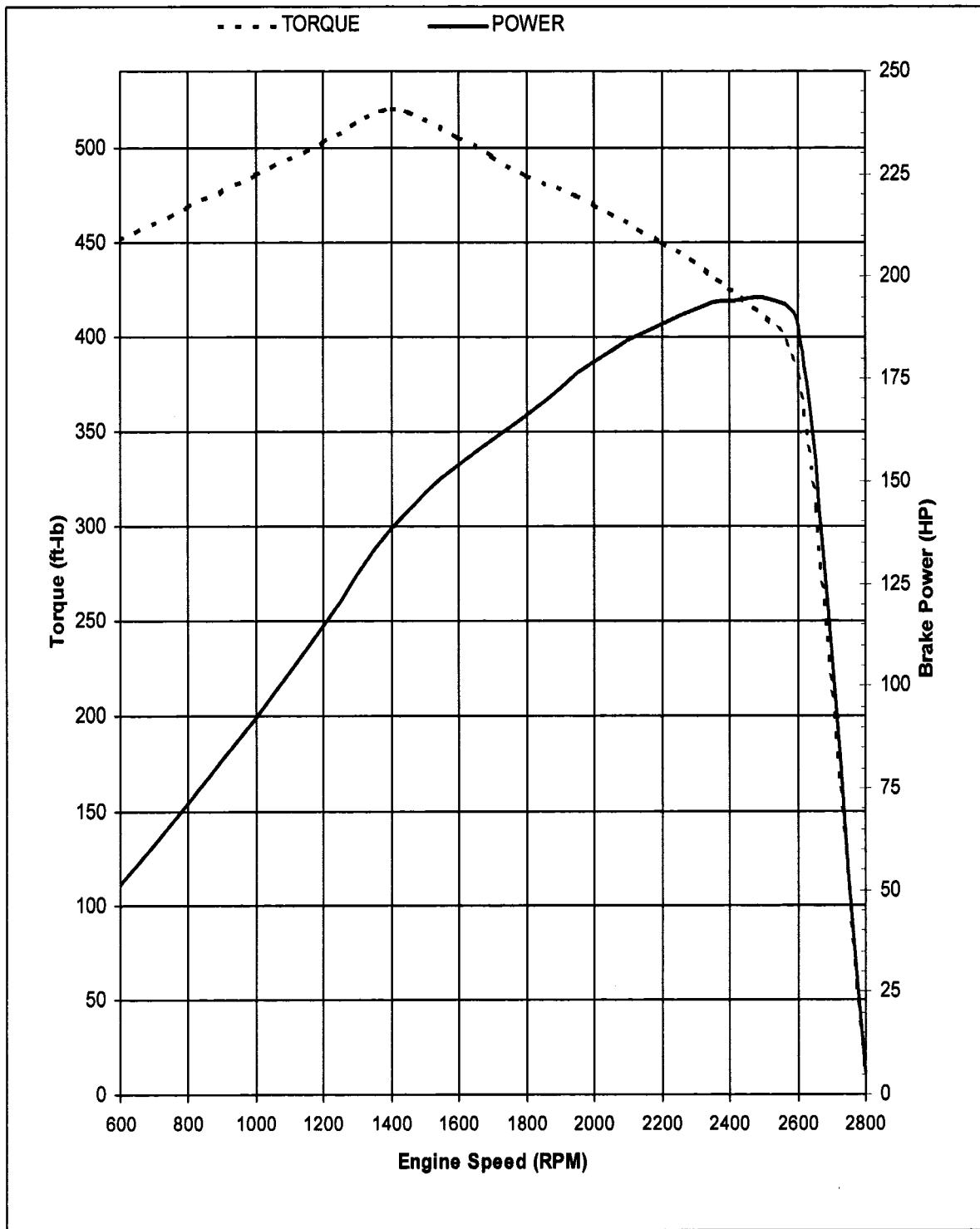


Figure 12: Cummins 5.9 L engine lug curve

2.3. Aberdeen Test Center

The Aberdeen Test Center (ATC) in Aberdeen, Maryland (50 miles North of Baltimore) is where the majority of school bus emissions testing for this project took place. ATC is a government owned and operated facility encompassing over 56,000 acres of various landscapes. For the purpose of this project, the main facilities used at ATC were their independent test track, an environmental chamber, and their precision fabrication machine shop. The ATC chemistry lab also provided fuel analysis for the various types of alternative fuels tested.

2.3.1. Test Track

A composite school bus testing cycle was conducted on the 1-Mile Loop Course at the Aberdeen Test Center. The testing course consists of a continuous asphalt surface with level, parallel 1/4-mile segments connected by 1/4-mile flat semicircular sections at each end. Use of the test track was employed with no other outside interruption, so the testing cycles were run smoothly with no outside interference.

2.3.2. Environmental Testing Chamber

As described in Chapter 5, school bus idle tests were also conducted at ATC. These environmentally controlled experiments were conducted in Environmental Chamber No. 4 at ATC. The environmental chamber is capable of controlling multiple climatic variables, including temperature, humidity, solar radiation, dust, icing, fog, and thermal shock. The test chamber has dimensions of 75 ft x 40 ft x 24 ft and can be divided equally into two smaller independent climatic compartments. One of these two independent climatic compartments was used for school bus testing. Temperature can be varied from -70 to 170 °F, and relative humidity can be raised to 98 %. Data acquisition

and control instrumentation are located in a separate room adjacent to the environmental chamber⁵³. Various views of chamber 4 are shown in Figure 13.⁵³

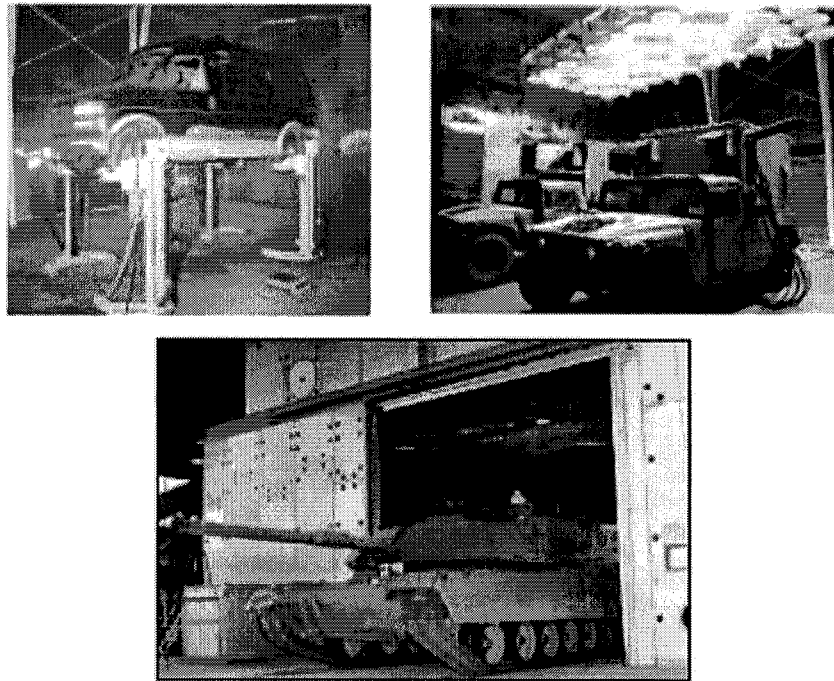


Figure 13: Environmental testing chamber 4

2.3.3. Chemistry Lab

The ATC Chemistry Fuels Testing Laboratory provided analysis on several properties of diesel fuels. The ATC Chemistry Team Laboratory is certified by the Army Petroleum Center as a fuel-testing laboratory.⁵³ The lab followed ASTM D975-01, Standard Specification for Diesel Fuel Oils, for the fuel testing. Properties of the fuels tested and the ASTM Method in which they were tested are as follows:

- Distillation range: The range of temperature, usually determined at atmospheric (Boiling Range) pressure by means of standard apparatus, over which boiling or distillation of a liquid proceeds., tested using **ASTM D 86**.
- API gravity: An arbitrary scale expressing the gravity or density of liquid

petroleum products, tested using **ASTM D 287**.

- Flash point (closed and open cup): The temperature at which a combustible liquid gives off just enough vapor to produce a vapor/air mixture that will ignite when a flame is applied, tested using **ASTM D 93**.
- Cetane index %: A calculated value, derived from fuel density and volatility, giving a reasonably close approximation to cetane number, tested using **ASTM D 4737**.
- Particulate contamination
- Sulfur Content, tested using **ASTM D 4294**.
- Cloud point: The temperature at which wax first becomes visible when diesel fuel is cooled under standardized test conditions.
- Pour point: The temperature at which the amount of wax out of solution is sufficient to gel the fuel when tested under standard conditions.
- Freeze point
- Fuel Viscosity, tested using **ASTM D 445**.
- Density or specific gravity, tested using **ASTM D 4052**.

2.4. Bus Instrumentation

Table 5 is a summary school bus emission testing instrumentation proposed for these tests. If a measurement was taken following an SAE standard testing measurement method, the method is noted in Table 5. Exhaust gas emissions measurements will include oxygen, CO, CO₂, NO₂, NO, SO₂, unburned hydrocarbons, and particulate matter. In addition to tail pipe emissions, the intake air, ambient air, school bus interior, and engine operating parameters were also monitored. The data was acquired using

several systems as described below.

2.4.1. Instrumentation Table

Table 5: School bus emissions testing instrumentation.

Sub-System	Measurements	Measurement System	SAE Standard	Sensor
Intake Air	Temperature	ADOCS	Yes J244	Thermo-couple Type K
	Humidity	ADOCS		Thermo-hygrometer
Ambient Atmospheric Conditions	Temperature	Semtech-D		
	Humidity	Semtech-D		
	Barometric pressure	ATC Post-Wide Meteorological System		
School Bus Exterior	Ambient Temperature Just Outside Bus	Semtech-D		Thermo Couple Type K
	Ambient Humidity Just Outside Bus	Semtech-D		Thermo-hygrometer
Engine	Crankcase temperature	ADOCS		Thermo-Couple on Dipstick Type K
	Vehicle Speed/ Distance	Semtech-D		GPS
	Engine Speed, RPM	Semtech-D	Yes J1003	ECM
	Exhaust Temperature 1	ADOCS		Thermo Couple Type K
	Exhaust	ADOCS		Thermo

Sub-System	Measurements	Measurement System	SAE Standard	Sensor
	Temperature 2			Couple Type K
	Exhaust Temperature 3	ADOCS		Thermo Couple Type K
	Throttle Position	Semtech-D		ECM
Exhaust Gas (Tail Pipe Emissions)	Oxygen	Semtech-D		Electrochemical sensor
	CO	Semtech-D	Yes J177	Non-Dispersive Infrared (NDIR)
	CO ₂	Semtech-D	Yes J177	Non-Dispersive Infrared (NDIR)
	NO ₂	Semtech-D	Yes J177	Non-Dispersive Ultraviolet (NDUV)
	NO	Semtech-D	Yes J177	Non-Dispersive Ultraviolet (NDUV)
	THC	Semtech-D	Yes J215	Heated Flame Ionization Detector (FID)
	PM	PM300		Photo Diode
Fuel	Mass flow rate Supply	ADOCS/ Cummins	Yes J1003	Flowmeter
	Mass flow rate Return	ADOCS/ Cummins		Flowmeter/ECm
	Chemical analysis of liquid fuel	ATC Chemical Lab		--
	Boost Pressure	Semtech-D		ECM

2.4.2. Electronic Control Module (ECM)

The Electronic Control Module (ECM) is an on-board computer system that

controls the opening and shutting of the intake and exhaust valves of an engine. The ECM is generally mounted near the engine in the engine compartment and reads a variety of signals. An ECM can also control engine performance parameters such as fuel metering, ignition spark advance, air-fuel mixture, and the engine-cooling fan. There are five individual parts to an ECM, the main one being the microprocessor. The microprocessor consists of Random-access memory (RAM), Read-only memory (ROM), Keep-alive memory (KAM), and several inputs and outputs.

Using an analog to digital converter, the ECM first converts information from the input sensors to a form that it can use to process the data. The information is then sent to the microprocessor where specifications that are stored in the memory chips are used to form an assessment of vehicle conditions based upon the engine's performance. This assessment is then sent to an actuator and an action occurs based upon the input of information. The final information can then be uploaded onto a device (such as the Semtech-D emissions unit read out screen) where the engine parameter information can be processed and analyzed. Several parameters can be read from the ECM microprocessor's RAM and KAM such as road speed, engine load, engine rpm, and fuel consumption. The main difference between the RAM and KAM is that KAM will store information even after the ignition is turned off.

Engine manufacturers have different service tools to access information from the ECM through a data link. A data link provides a physical means for transmitting and sorting electric signals. A data link consists of special electronic circuitry and electrical connections. Connection points for electronic service tools are also part of the data link. A data link adapter is a device that converts the SAE J1587/SAE J1708 or the SAE J1939

data link messages from the ECM into a message that a personal computer can understand. The Sensor's Inc. Semtech-D emissions analysis equipment connects to the ECM in a similar manner. The NEXIQ Corporation SDM network interface for heavy-duty diesel engine interfaces is used to connect the ECM to the Semtech-D. The SDM interface has been developed and validated on all SAE-J1708/SAE-J1587 equipped diesel engines, which comprises the majority of the fleet.⁵⁴

2.4.3. Sensors Inc. Semtech-D

The Sensors Inc. SEMTECH-D (Sensors Emissions TECHnology-Diesel) mobile emissions analyzer was chosen as the main emissions measuring device for this project. The Semtech-D is a portable Windows PC based data acquisition system capable of measuring emission levels along with several vehicle and engine parameters. Installing the unit on a school bus takes less than half an hour and requires very few installation tools. The Semtech-D unit incorporates a variety of stand-alone emissions measurement devices to monitor THC, NO, NO₂, O₂, CO, and CO₂ emissions. Since the Semtech-D is a portable unit (78 lb. approximate weight), all of the emissions sensors were modified by Sensors, Inc. by either some or all of the following ways: a reduction in size or weight, decreased power consumption, or reduced sensitivity to vibration and changes in ambient temperature, pressure and humidity.⁵⁴ A front panel display of the Semtech-D mobile emissions analyzer can be seen in Figure 14. An important quality of the Semtech-D unit is the vehicle interface that allows the unit to retrieve engine and vehicle information from the ECM. A heated line is used to collect emissions from a probe located in the tailpipe with the following sensors (the internal sensors can be seen in layout format in Figure 15).

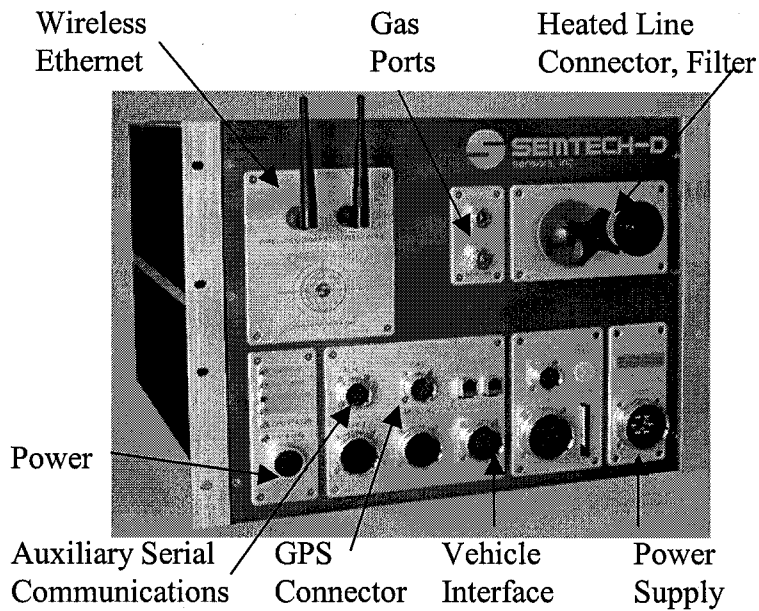


Figure 14: Sensors inc. Semtech-D mobile emissions analyzer

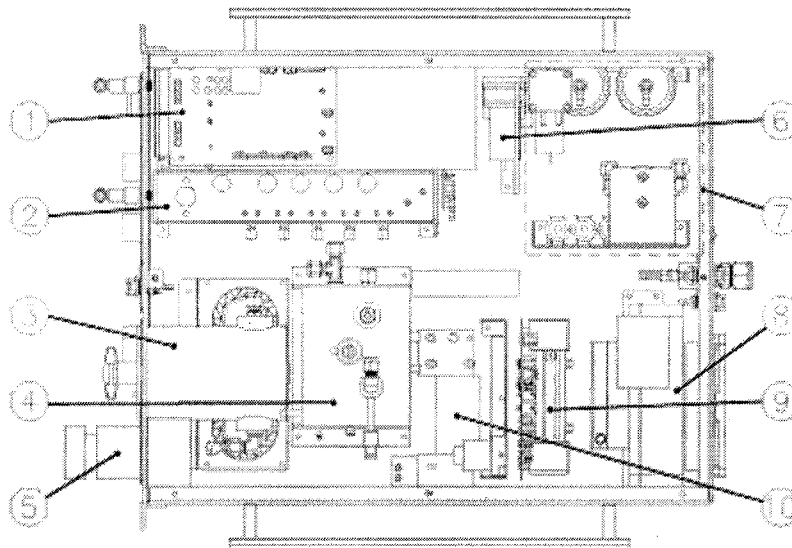


Figure 15: Internal layout of Semtech-D unit⁵⁴

Provided below is the layout description in conjunction with Figure 15:⁵⁴

1. Non-dispersive ultraviolet NO/NO₂ analyzer.
2. Pneumatic control panel. This contains pressure regulator, solenoid valves, and

needle valves that control the sample to the analytical instruments.

3. Internal Heated Filter. This chamber is heated and controlled to 190 °C, and holds a replaceable, 0.1 micron filter element to remove particulates from the exhaust stream. The filter is accessed from the front panel.
4. Heated FID chamber. This assembly houses the FID chamber and solenoid valve. The entire assembly is heated to 190 °C and insulated.
5. Heated line connection.
6. Sample and drain pumps. These pumps provide a cooled, dry sample to the CO₂/CO, O₂, and NO/NO₂ analyzers. The two drain pumps remove water and by-pass sample from the chiller and coalescing pre-filter.
7. Filtration. Two Carbon filters remove hydrocarbons from the ambient air port on the rear panel, and from the FID combustion air. A coalescing pre-filter removes excess moisture from the sample before it enters the chiller. In-line particulate filters protect the pumps and analytical instruments. All filters are disposable.
8. Thermo-electric chiller. This device cools the sample in order to condense water and heavy hydrocarbons before entering the CO₂/CO, O₂, and NO/NO₂ analyzers. The chiller cold-plate is controlled at 4 °C.
9. Non-dispersive infrared CO/CO₂ analyzer
10. FID heated sample pump

Most mobile emissions analyzers on the market are composed of a network of stand-alone sensors. The emissions needed for collection are NO, NO₂, O₂, CO₂, CO, and total Hydrocarbons (THC). Each chemical detected has an important function for data recording, calculations and consequences when released into the atmosphere. The

Semtech-D uses a heated, insulated sample line to reduce the loss of THC. The heated line is twelve feet in length and operates at 191 °C. Teflon is used as the wetted surface of the line because of its high heat resistance and low absorbing properties. A heater is wrapped around the Teflon line, which is molded inside a larger insulated flexible tube.⁵⁴ The heated line is filtered at the inlet to prevent contamination from particulates.

Oxygen (O₂) is one of the two important reactants for internal combustion in air. O₂ concentration is read using an electrochemical sensor by the Semtech-D gas analyzer. Electrochemical sensors require the sample to be dry before passing over them. The sensor detects the partial pressure of O₂ in the stream and reports it electronically. This technology is used in prior emission measurement devices and gas analyzer companies are attempting to produce products that can continuously give accurate data. Other emissions can also be measured using electrochemical sensors, but more advanced techniques have been developed and are being used by the Semtech-D.

Sensors Inc.'s Non-Dispersive Ultraviolet (NDUV) system is currently the newest technology for NO_x. Sensor Inc. employs a dual NO and NO₂ detection system based on a plasma powered ultraviolet light to detect NO and NO₂ separately. Previous attempts at ultraviolet detection were hindered by the life of the ultraviolet light. The NDUV sensor does not deteriorate like the electrochemical does over time. The most important condition of NO_x detection is the removal of water before the sensor where the exhaust sample is dried with an ambient temperature coalescing filter followed by a thermoelectric chiller. The heavy hydrocarbons found in the diesel exhaust sample are removed from the sample along with a small amount of NO₂ (about 5% of sample) with the water removal process to prevent contamination of the optics.

The NDUV operates at a rate of 2 Hz to collect the continuous concentration measurements for NO and NO₂ to the Semtech-D data collection software via an internal EIA-232 serial connection.⁵⁴ The NDUV has an accuracy of 15 ppm, or 3 % of the reading for NO, whichever is greater, and 10 ppm, or 3 % of reading for NO₂, whichever is greater, when properly calibrated at a range of 0 – 5000 ppm and 0 – 500 ppm, respectively, and zeroed prior to a test.⁵⁴ Sensors Inc. conforms to the CFR 40 86.1342-90 standard for measuring NO_x, using the following equation.¹⁹

$$NO_{x\ mass} = K_H \times \sum_{i=1}^n \left[\frac{(NO_{x\ dry})_i}{10^6} \times (V_{mix})_i \times \rho_{NO_2} \times \Delta T \right] - K_H \times \frac{NO_{x\ d}}{10^6} \left(1 - \frac{1}{DF} \right) \times V_{mix} \times \rho_{NO_2} \quad 1$$

where NO_{x mass} is the oxides of nitrogen emissions (grams per test phase), ρ_{NO₂} the density of oxides of nitrogen (1.913 kg/m³ assuming they are in the form of nitrogen dioxide at 20 °C and 101.3 kPa pressure), and NO_{x dry} the oxides of nitrogen concentration of the dilute exhaust bag sample as measured (ppm). For flow compensated sample systems (NO_{x dry})_i is the instantaneous concentration. NO_{x d} is the oxides of nitrogen concentration of the dilution air as measured (ppm), V_{mix} the total dilute exhaust volume (cubic feet per test phase corrected to standard conditions 293 °K and 101.3 kPa, ΔT the change in temperature, and K_H the humidity correction factor. To obtain the KH to convert from wet NO_x to dry NO_x the 1973 SAE standard⁵⁵ is utilized:

$$NO_{corr} = \frac{NO_{wet}}{K_H} \quad 2$$

$$NO_{wet} = NO_{dry}(ppm)[1 - \alpha(F/A)] \quad 3$$

$$K_H = 1 + 7 * A(H - 10.714) + 1.8 * B(T - 29.444) \quad 4$$

$$A = 0.044(F/A) - 0.0038 \quad 5$$

$$B = -0.116(F/A) + 0.0053$$

6

where NO_{dry} is the measured NO_x emissions (ppm), α the atomic hydrogen to carbon ratio (y/x in fuel with formula C_xH_y), F/A the fuel to air ratio (Dry Basis), H the specific humidity (grams of H_2O /kg dry air), and T the intake air temperature ($^{\circ}C$). The temperature range for this correlation to work effectively is 70-115 $^{\circ}F$. Ambient and intake temperature and humidity are measured mainly for this reason. As described in Chapter 5, a new correction was developed specifically for use with the school busses tested here.

The AMBII Non-Dispersive Infrared (NDIR) analyzer is used by the Semtech-D to measure CO and CO_2 emissions. This sensor also needs the incoming gas dried to remove heavy hydrocarbons and water vapor that cause interference with the sensor. The gas is dried in the same manner as the NO_x analyzer with an ambient temperature coalescing filter followed by a thermoelectric chiller. If the gas were not dried interference would occur in the infrared channels. Unlike the NO_x emission, the CO_2 and CO emissions do not require humidity corrections. The AMBII NDUV operates on a continuous .83 Hz (1.2 second) data rate to collect concentration measurements of CO and CO_2 to the Semtech-D data collection software via an internal EIA-232 serial connection.⁵⁴ The AMBII NDUV has an accuracy of 50 ppm, or 5 % of reading, whichever is greater, when properly calibrated at a range of 1200 – 1500 ppm and zeroed prior to a test.⁵⁴

While infrared and electrochemical cells may work for HC detection, the Flame Ionized Detector (FID) employed in the SEMTECH-D is superior in measurement

sensitivity. While keeping a flame lit with hydrogen, a sample is passed over and combusted. The concentration of the HC is then determined by the amount of sample that burns. The FID fuel used for FID flame ignition is a 40/60 mixture of hydrogen/helium. The user can also select a data rate of up to 4 Hz through the Semtech-D application software. The AMBI NDIR has an accuracy of 5 ppm, or 1 % of reading, whichever is greater, when properly calibrated at a range of 0 – 100 ppm and zeroed prior to a test.⁵⁴

In order to calculate the widely accepted emissions units of grams per mile and grams per brake horsepower, fuel flow rate is needed. Using injector pore size, the ECM can measure fuel flow rate, which is the procedure used by Sensors Inc for Semtech-D.

Semtech-D relies on the ECM to provide fuel flow information in order to calculate fuel flow rate and time specific mass emissions. The ECM determines the fuel flow rate based on the real-time pulse width of the fuel injectors.⁵⁴ Transient mass emissions are thus calculated by multiplying the fuel specific emissions by the fuel flow rate (NO₂ for example) as follows:

$$\text{NO}_2 \text{ (g/s)} = \text{NO}_{fs} \text{ (g_NO}_2\text{/g_fuel)} \times \text{Fuelflow (g/s)} \quad 7$$

The total fuel consumption can then be calculated instantaneously from the volumetric fuel flow rate and fuel density, which is supplied by the user. The ATC Chemical lab provided fuel density of the fuels tested for this purpose. The fuel flow method of computing mass emissions, CFR40 part 86.345-79 describes the fuel flow method for mass emissions computations for diesel engine dynamometer testing, which is what was used here. The Semtech-D unit also calculates torque to use for calculating emissions in g/bhp-hr. Direct torque output is not available for any of the school buses used in this

project, so engine torque was computed by applying the percent load parameter with an engine lug curve (maximum torque curve). The percent-load parameter is defined as:

$$\% \text{ Load} = (\text{current engine torque}) / (\text{maximum engine torque})$$

where the maximum engine torque is defined at the current engine RPM provided by the ECM. The engine lug curves for the three buses tested were supplied by the engine manufacturers International and Cummins. The lug curves define the maximum engine torque for all engine speeds. Examples of engine lug curves for the engines tested can be seen in Figure 10, Figure 11, and Figure 12. Using the fuel flow rate and torque measurement it is possible to provide g/bhp-hr emissions units.

The Semtech-D unit is equipped with a compact flash reader, 2 Ethernet connections, 3 RS-232 connections, an RS-485, and two wireless connections. The two wireless connections are designed for use with a laptop computer, and a personal desktop assistant (PDA). The Semtech-D uses a graphical user interface (GUI) for control, monitoring, and analysis of the data collected by the unit. The GUI is displayed on both the laptop screen and the PDA screen while the unit is in use. The data collected is stored in two locations in the Semtech-D. At the end of the test, the run data is loaded onto the laptop and a copy of that data is saved on the compact flash card located on the front panel of the Semtech-D. To validate vehicle speed from the ECM, an external GPS device accompanies the Semtech-D. This device mounts outside of the vehicle to maximize reception. When the data is processed, both ECM speed and GPS speed are represented as columns in Microsoft Excel.

The Semtech-D can be calibrated at any time prior to actually running a test. The unit contains 4 inputs for gas: the ambient port, span/audit port, the sample port, and zero air

port. The audit gases are run before and after a test is performed to ensure the sensors are still reading accurately. The user has the option of recording the audit at all times. The span gas is used before a test to calibrate the CO, CO₂, NO, NO₂, and/or THC sensors. The zero air port (pressure regulated) and ambient port (unregulated) is used before a test to calibrate the O₂ sensor. The sample port audits gas through the heated sample line and can be used for any gas channel. For this project the span and zero air ports were used for calibration. The procedure used for the sensors for start-up of the unit is as follows:

1. A zero calibration is performed after the equipment has been properly warmed up. A zero is performed at the beginning of every test day.
2. An audit is performed at the beginning and end of every test to ensure analyzer accuracy. Gas bottles with known concentrations are used for the audit, where the all sensors must meet specified tolerances for a successful test.
3. If any gas channels fail the audit, a span is necessary. A gas bottle of known concentration is used and programmed into the Semtech-D unit. The unit uses the known value to recalibrate the sensor.
4. After the zero, audit, and span if necessary operations are completed a test is ready to be performed. After the test it is useful to perform another audit to check the sensors for drifting. If any audit fails, the test will be discarded.

The Semtech-D uses a Vehicle Interface (VI), which is not always common in emission gas analyzers. However, communicating with the engine's ECM through the VI allows the user to calculate the emission rates in grams per brake horsepower-hour, and

grams per mile, which are currently the emissions units used by the EPA. The Semtech-D has the capability of connecting to the ECM, providing the vehicle has one, and reading the data the ECM sends out. Common measurements read from the ECM include vehicle speed, engine RPM, and fuel flow rate. All ECM's must meet SAE programming standards, which enables gas analyzer companies to connect to all engine manufacturer's ECM's with very few connectors.

The VI is also important for Semtech-D to allow the user the ability to follow a prescribed drive cycle on the PC screen. The user imputes a prescribed driving cycle into the Semtech-D software. The target vehicle speed vs. time curve from the prescribed drive cycle is graphically displayed as a line along with the actual vehicle speed, which is shown as a large dot. The driver of the bus attempts to line up the instantaneous dot (actual speed) with the prescribed line (target speed) in order to accurately follow the drive trace. A digital display is also included on the screen that shows the vehicle's actual speed, target speed, time elapsed and remaining, as well as the total drive cycle time.

2.4.4. Sensors Inc. PM-300

Particulate Matter was measured using a Sensors Inc. PM-300. The PM-300 is a portable particulate analyzer, which uses a light scattering technology to count particles.⁵⁶ A semiconductor-laser emits a beam of light through the exhaust sample, which is carried via a heated hose to carefully control humidity and temperature and then diluted to a ratio of 1000:1, 2000:1, 5000:1, or 10,000:1, depending on the particle sizes being measured. The light is then detected by a photo diode at approximately 90° by way of mirror that is interrupted by the passing particles. Each particle creates a pulse in the beam, which is directly proportional to its size. This signal is then classified into size categories and

stored for later download to a computer for analysis. The PM-300 also collects the particulate on a PTFE filter that can be removed for analysis. The PM-300 unit uses a similar twelve-foot heated line as the Semtech-D unit to preserve the integrity of the sample out of the tailpipe and into the unit. The PM-300 can be seen in Figure 16.



Figure 16: Sensor's Inc. PM-300 particulate analyzer

Unlike the Semtech-D, the only pre-test requirement for the PM-300 is to allow the heated sample line to reach a desired temperature of 200 °F. As stated earlier the PM-300 measures particulates in bins relating to the size of the particulate measured (0.3 micron to 2 micron in 8 bins (0.3, 0.4, 0.5, 0.65, 0.8, 1.0, 1.6, 2.0 microns)). Each bin is recorded on 1-second intervals and is time stamped. The PM-300 measures particulate by the total number of particulates per liter for the particular bin size. To convert from number of particulates per liter (#/L) to g/hr, number of particulates per liter is multiplied by the particulate density (g/m^3), volume ($\text{m}^3/\text{#}$) (assuming spherical geometry =

$4/3(\pi) r^3$), and dilution ratio (L) of the given particle. The PM-300 uses a dilution ratio of 1000 L. An example of an Excel graph of PM data from the PM-300 is shown in Figure 17.

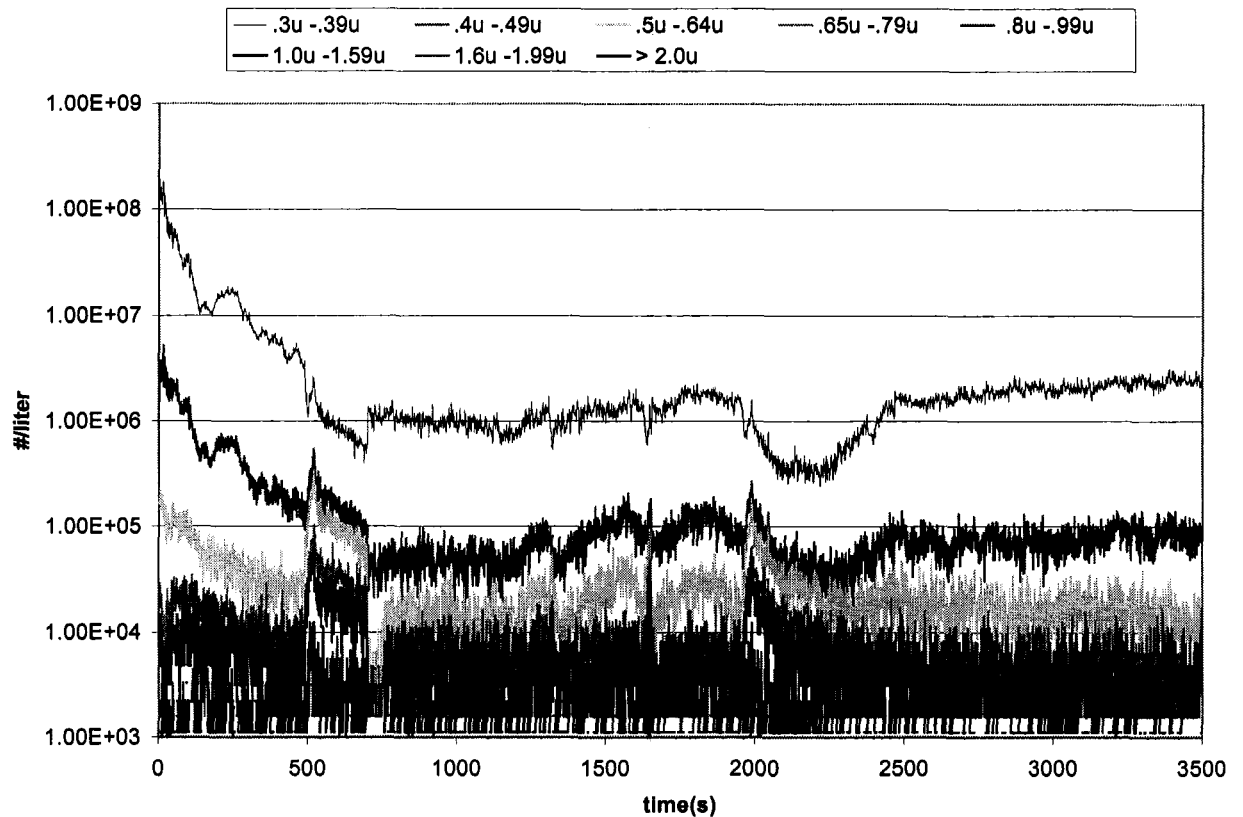


Figure 17: Excel graph of PM data separated by bins

2.4.5. ADOCS ATC Data Acquisition System

The ADvanced Onboard Computer System (ADOCS) data acquisition system was used by ATC to combine 32 inputs into one continuous stream. ADOCS was designed by ATC for testing parameters off of any vehicle particularly army type vehicles. Due to the military application ADOCS was built to be very ruggedized. The system is based on the 32 bit Motorola family of processors and 3U size VME bus circuit cards.⁵⁷ ADOCS was used to measure vehicle and engine parameters not provided by the ECM or the Semtech-D unit. ADOCS data is formatted in ATC's Universal File Format (UFF),

which can be easily converted to an Excel spreadsheet. ADOCS operates using a Windows based user interface for easier interaction. An ADOCS Signal Conditioning System (ASCS) is used to condition each of the 32 ADOCS channels being used. The ASCS accepts inputs from pressure sensors, thermocouples, and displacement sensors as well as outputs from pulse instrumentation and provides signal amplification, filtering, and calibration.⁵⁷ The complete ADOCS and ASCS system weighs approximately 32 lbs. and dimensions of 9 inches width, 10.3 inches high, and 17 inches deep. A complete ADOCS unit is shown in Figure 18.

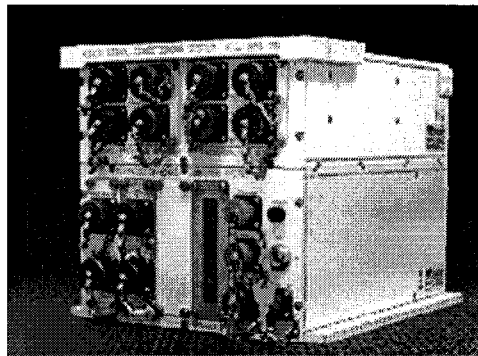


Figure 18: ADvanced Onboard Computer System (ADOCS)

For the purpose of school bus emissions testing, ADOCS was used for only a few parameters. The Cummins bus had a fuel flow rate meter installed due to the lack of an ECM. The fuel flow rate was recorded by ADOCS. Three thermocouples were used in conjunction with ADOCS to measure the exhaust temperature at three distinct locations along the tailpipe. The temperature at these locations are pertinent when designing particulate traps where temperature can be an important factor.

2.4.6. Data Management

An important part in analyzing the data collected from up to three separate instrument platforms is making certain the data is correctly referenced in time. All three units were

started at approximately the same time and all three units report data at 1 Hz. The Semtech-D reports all of its data by exporting it directly into a single Excel spreadsheet. The PM-300 provides a text file, which can be turned into a comma delimited Excel file rather easily. ADOCS data is reported in Universal File Format (UFF), which also can be quickly converted into an Excel spreadsheet. Since, for example, percent load (reported by Semtech-D) is important in the concentration of particulates (PM-300) it was important to have all data in a single Excel spreadsheet. All three pieces of equipment provide time stamping, which is a definitive way to reference all three Excel files compiled from the equipment into one single file for the analysis.

Data collected by ATC personnel during testing was sent electronically to Rowan for analysis. Included with all data was a running log file that was up to date with the current data being forwarded. Every log consisted of the following data: day of test, time of test start and end, daily run number, fuel type, school bus type tested, equipment used, school bus driver, success of audits, and any additional comments to describe the test run. The data was then separated into folders named according to date and then data type (e.g. PM-300, Semtech-D, audit, etc.).

3. Development of a New Mobile Emissions Test Cycle for School Buses

3.1. Introduction

This chapter describes the development of a new mobile emissions test cycle for school buses. Also provided in this chapter is a literature search of previous test cycles, a demographic breakdown of regions in NJ, and detailed bus routes of various NJ school bus districts.

Federal regulation requires that all heavy-duty diesel vehicles (HDDV) complete an engine certification process using the Transient FTP engine dynamometer cycle.⁵⁸ Several emission-testing cycles, such as the Transient FTP, have been developed for federal and private emission testing purposes. These HDDV testing cycles are based upon speed versus time traces. Traditionally, diesel engine emissions are measured using a cycle in a stationary position with the engine either in a vehicle on a chassis dynamometer or the engine alone using an engine dynamometer (See Chapter 1). Mobile emissions' testing consists of the engine emissions being measured from the mobile vehicle being tested on the road. There are presently emission test cycles developed for transit buses and delivery trucks, which are not approved or adopted by the EPA, using a chassis dynamometer for the testing, but no cycles have been created for mobile testing.

Prior to the present study there existed a scarcity of emission test cycles developed specifically for school buses. Moreover, mobile-on-road or in-use emissions testing is relatively new to the emissions testing field, so a standard test cycle for mobile school bus emissions testing was not available. Accordingly a new standard test cycle for mobile school bus emissions testing was developed as part of the present study. The Rowan

University Composite School Bus Cycle (RUCSBC) was developed using actual global positioning system (GPS) data from a variety of prototypical New Jersey school bus routes. The school district routes were chosen based upon the population density of the district, school age children population of the district, the total number of the district's buses, and the total number of students in the district. The RUCSBC can be broken down into three sections to represent the three common areas of the state: rural, suburban, and urban. As described below, the RUCSBC was used to simulate a typical New Jersey school bus route in order to compare baseline emissions to emissions with a variety of fuel types.

3.2. Literature Review

The 2007 HDDV emission standards have lead to extensive testing of the vehicles and their engines on both chassis and engine dynamometers. The extensive testing has led to an increasing number of test cycles being created to represent some type of driving pattern for the HDDV industry. Only a few test cycles have ever been created using actual data collected from the vehicle during its normal operation. To date there has also been no test cycle known created specifically for school bus mobile emissions testing. This literature search is provided to show the function of current emission test cycles, how the cycles were developed, and what the cycles were developed for.

West Virginia University (WVU) developed a route for delivery trucks using data from actual delivery truck routes. The City Suburban Heavy Vehicle Route (CSHVR)⁵⁹ was designed to consider power-to-weight ratio of the vehicle running the route. A route differs from a cycle in that a route allows the full power of the vehicle being tested to be employed.⁵⁹ In a route the vehicle follows a speed vs. distance trace allowing vehicles

with the ability of more rapid accelerations to finish the route in less time. A cycle is a speed vs. time trace and should be completed in the same amount of time by every vehicle regardless of its power or size.

The CSHVR was developed from data collected from Classes 7 and 8 delivery trucks (from two different trucking companies, one based in Akron, Ohio and one from Richmond Virginia). Speed vs. time data along with video recordings were collected for the trucks for a total of approximately 60 hours. The data was broken down into a total of 130 microtrips. The definition of a microtrip for this route was defined typically as driving from one delivery site to another. The 130 microtrips were further separated into categories: interstate freeway, suburban, city, and yard with the aid of the video taped data.

All of the microtrips from the CSHVR were analyzed to determine the percentage of time when the vehicle was accelerating, decelerating, and cruising. The idle time and average velocity for each microtrip was also taken into account. The microtrips were then randomly selected and concatenated using a computer program yielding 10,000 possible combinations. The constrained time range of the cycle was 1000-1600 seconds. The most representative cycle was then determined using a route mean squared (rms) approach using the following parameters: standard deviation of speed, average speed, and percent cruise time. Each of the parameters chosen for the most representative cycle was weighted evenly. These were all compared to the desired database values for each category. The cycle with the lowest rms was chosen as the most representative cycle. When performing the analyses, the idle time was removed and then added back in at the end so that only the vehicles motion was characterized. In the WVU, individual driver

habits determined the amount of idle time the vehicle would incur (whether or not they would leave his/her vehicle on during deliveries, etc.). The CSHVR is shown in Figure 19.

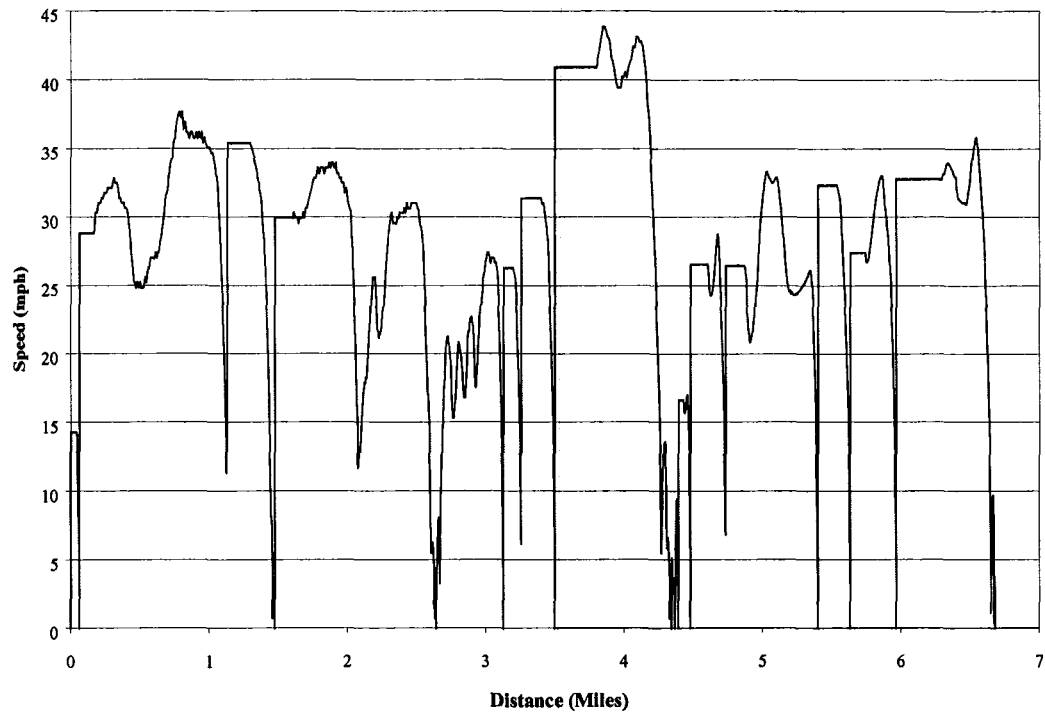


Figure 19: City Suburban Heavy Vehicle Route

Three additional cycles were developed by WVU using the same procedure discussed for the CSHVR: the Yard, City-Suburban, and Freeway cycles. There is also a discussion of driver repeatability and positive comparison between different drivers performing the same cycle in reference to output emissions. These results include discrepancies of 11.1% for CO and 14.8% for PM, which were the emissions most influenced by using various drivers (NO_x emissions varied slightly).

National Environmental Protection Council Service (NEPCS) presented a method used to take real driving data and construct a representative cycle. In creating a representative cycle, the trips (velocity vs. time data collected) were separated into

microtrips similar to the WVU study. The definition of a microtrip is a period of idle, followed by a period of driving activity until it again comes to rest, whereupon a new microtrip begins.⁶⁰ The idle periods at the ends of a driving trip were not analyzed as microtrips, but were factored into the representative cycle at the end. The two most important variables chosen in classifying road trips were average speed and idle time.

Some statistical information was then calculated for each microtrip and they were separated into the following categories: congested, residential/minor, arterial, and freeway/highway. In the NEPCS study, the most representative microtrips were those that spent time at speeds and accelerations in similar proportions to those of all the microtrips combined. The chosen microtrip was the one that minimized the empirical distribution function between it and all of the microtrips. However, the length of the idle period was also factored into and weighted heavily into representative microtrip selection.

One of the earliest and a well-documented heavy-duty vehicle cycle was developed for city buses. The “Central Business District” (CBD) Cycle (SAE recommended practice J1376) was developed to simulate heavy-duty buses during inner-city operation. This test is well established and, arguably, accurately accounts for the exhaust emissions from heavy-duty inner-city buses (Clark et al., 1994). The CBD Cycle consists of 14 accelerations and 14 steady state operation periods at 20 mph each followed by a deceleration and an idle period, as depicted in Figure 20. Total traveled distance for the CBD is 2 miles. There are a few disadvantages of the CBD that tend to limit its use beyond inner-city buses. One of these disadvantages of the CBD is the high acceleration rates with the cycle. A typical class 8-road tractor with an unsynchronized transmission

could not follow the CBD acceleration ramps successfully (Clark et al., 1994). The Central Business District (CBD) Cycle is a chassis dynamometer testing procedure for heavy-duty vehicles (*SAE J1376*). The CBD cycle represents a “sawtooth” driving pattern, which includes 14 repetitions of a basic cycle composed of idle, acceleration, cruise, and deceleration modes.

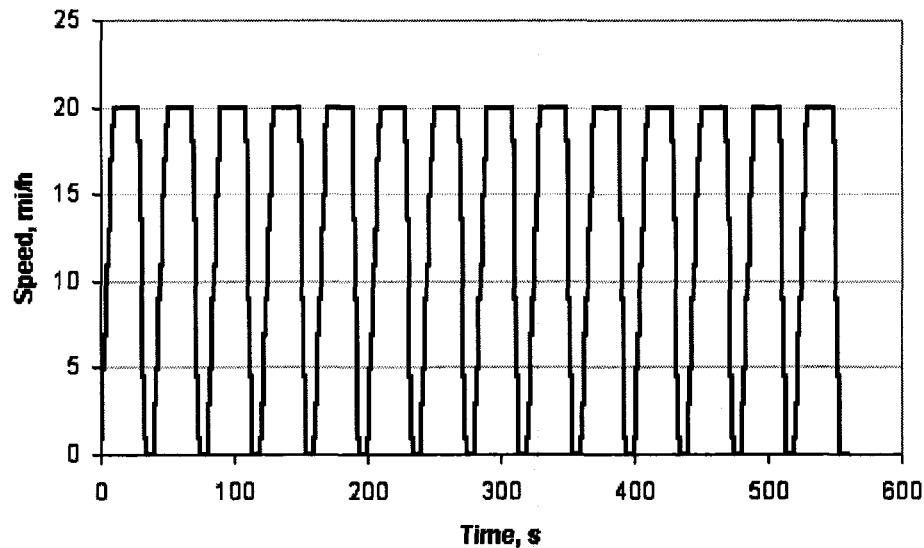


Figure 20: Central Business District Cycle

3.3. Procedure for Generating a New Mobile Cycle

The first step in generating the mobile school bus cycle was to take actual GPS data from a variety of prototypical school districts in NJ. In each case, a Garmin GPSMAP 765 Global Positioning System was placed on the school bus and activated at the beginning of a normal bus route and stopped when the bus returned to school. There were a total of five school bus districts examined from three different counties. These districts were as follows: Deptford (Gloucester County), Pittsgrove (Salem County), Medford (Burlington County), Washington Township (Gloucester County), and Glassboro (Gloucester County).

In total, data from 11 different school bus routes (each referred to as a single “trip”)

were acquired. Each trip was then separated into microtrips (sometimes called a sequence). Each microtrip (or sequence) consists of a period of idle, followed by a period of acceleration and deceleration, until the bus again comes to a complete stop at which time the next microtrip starts.⁶¹ A total of 135 individual microtrips were generated from the data. In addition, most of the trips contained a period of idle at the end. For simplicity, the idle times were not included in any of the statistical analyses, but were later factored into the developed cycle to accurately represent the typical idle a school bus would incur.

3.3.1. Types of School Districts /Regions

The microtrips were separated into three categories based on the average speed of the microtrip. Category A included the microtrips with a mean speed range of 0-20 mph, category B a range of 20-35 mph, and category C a range of 35+ mph. Since idle is very important in characterizing school bus driving behavior (typically many stops for child pick-up/drop-off), idle were used in calculating the mean values of microtrip speed, thus slightly reducing the averages.

Each of these categories (A, B, and C) were designed to represent a different type of region in NJ: urban, suburban, and rural. An urban area would be considered to be most densely populated and would reside predominantly within category A. Glassboro and Washington Township (both located in predominately urban Gloucester County) are classified as urban areas according to the NJ State Data Center 2000 report.⁶² These urban area microtrips therefore have the lowest mean speed, the shortest duration, shortest distance, and the largest percent of idle time at the beginning of each microtrip (signifying more stops, made more often, with more children at each stop).

Category C microtrips represented the rural area in NJ, which are the least densely populated areas. The rural areas of NJ were characteristic of having the highest mean speeds, the longest duration, the longest distances, and the shortest idle times (signifying fewer stops that are further apart with less children at each stop). Pittsgrove, located in predominately rural Salem County, has the lowest population density of the data taken and is classified as mostly rural by the NJ State Data Center 2000 report.⁶²

Those microtrips belonging to category B were considered suburban and its statistical characteristics fell in between categories A and C. Deptford is classified by the NJ State Data Center as mostly urban, however statistical data from the school bus routes places the Deptford runs mainly in the suburban category for the cycle development purpose. Medford, which is located in the mixed, urban and rural, Burlington County also contains some urban and some rural population. Medford also has the second lowest population density of the GPS taken and was classified as suburban for the purpose of the RUCSBC development. A breakdown of the rural and urban districts are shown in Figure 21, which is provided by the U.S. Census Bureau, with the urban areas shaded. A population and demographic breakdown of the five districts for which data was collected is shown in

Table 6.

Table 6 Prototypical NJ School Bus Districts^{62,63}

District	Medford	Washington Twp.	Glassboro	Pittsgrove	Deptford
Population	22,253	47,114	19,068	8,893	26,763
Population Density People/Sq. Mile	561	2091	1898	195	1414
Amount of Rural Population	2,690	0	252	5,907	0
Amount of Urban Population	19,563	47,114	18,816	2,986	26,763
Number of Students	2949	9761	2518	1878	4107
Number of Schools in District	5	11	5	4	9
Number of Buses in District	30	73	23	27	41

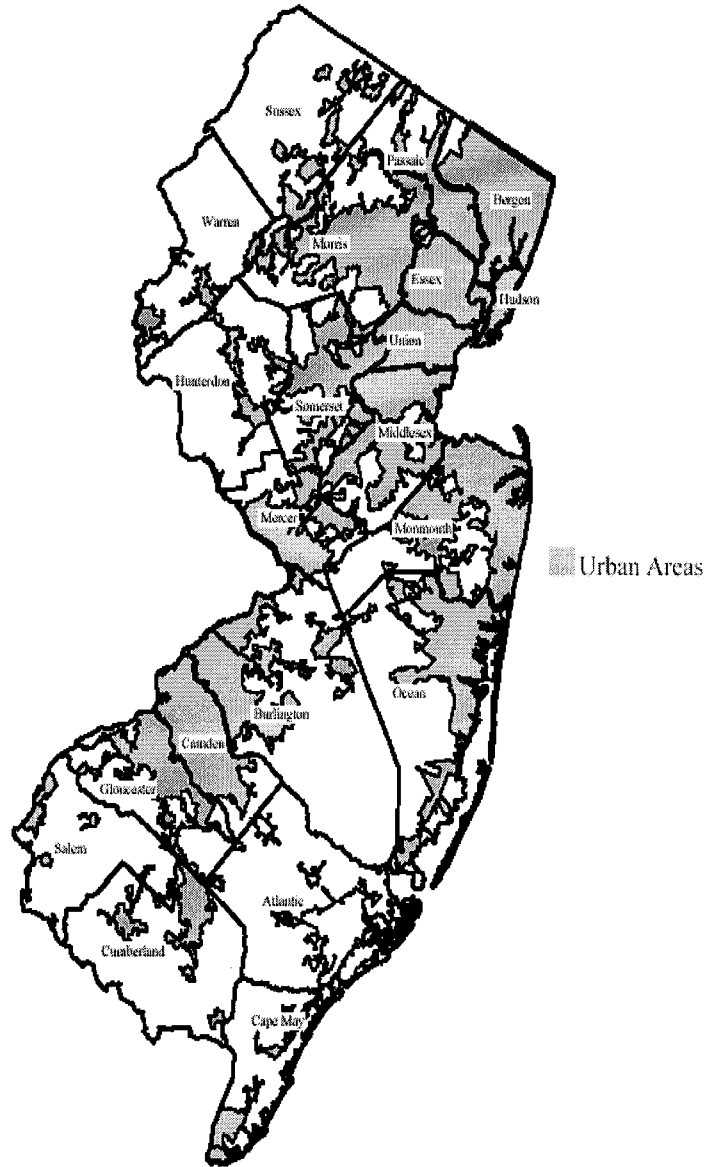


Figure 21: New Jersey Population Breakdown by Urban and Rural Regions⁶²

3.3.2. GPS Mapping: Experimental Procedure

The Global Positioning System (GPS) used for school district route data acquisition was a Garmin GPSMAP76S. The GPS used for data acquisition is capable of acquiring up to 500 waypoints and about one hour of data before loading the data onto a computer. The unit has a position accuracy of approximately 15 m and a velocity accuracy of 1.15 mph. Data is processed using Excel and the Garmin supplied software Map Source. The

GPS transfers data to a PC in the form of an Excel file, which includes the following information: position, altitude, time, leg length, leg speed, leg time, total time, average speed, and leg course. The Garmin GPSMAP76S unit is shown in Figure 22.

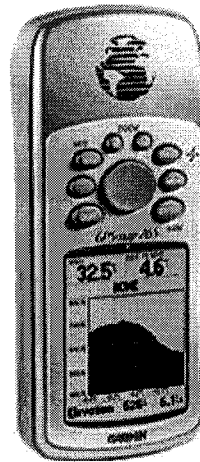


Figure 22: Garmin GPSMAP76S

The GPS was placed on the school bus for each respective district. Data acquisition started when the school bus driver started the bus for their route and ended when the school bus was turned off for the same route. Waypoints were taken at specific locations to mark the route and the school bus stops. The GPS was then connected to the serial port on the computer through a PC cable and data was transferred in text format for analysis. Data to create the cycle was taken in the form of a speed vs. time drive trace. The speed vs. time drive traces for the Medford, Washington Township, Glassboro, Pittsgrove, and Deptford school districts are shown in Appendix A.

In a similar format to the drive traces, data was transferred to the Map Source software provided by the Garmin Company, which created an actual map of the school bus route. The map created by the Map Source Software is similar to a common road map except the drive trace of the school bus is highlighted and the school bus stops are marked. Two maps are shown for the Washington Township and Pittsgrove school

districts Appendix A. Note that the Washington Township map contains three separate runs consisting of an elementary, middle, and high school route. Figure 23 and Figure 24 are examples of typical map and speed vs. time traces acquired during testing, respectively.

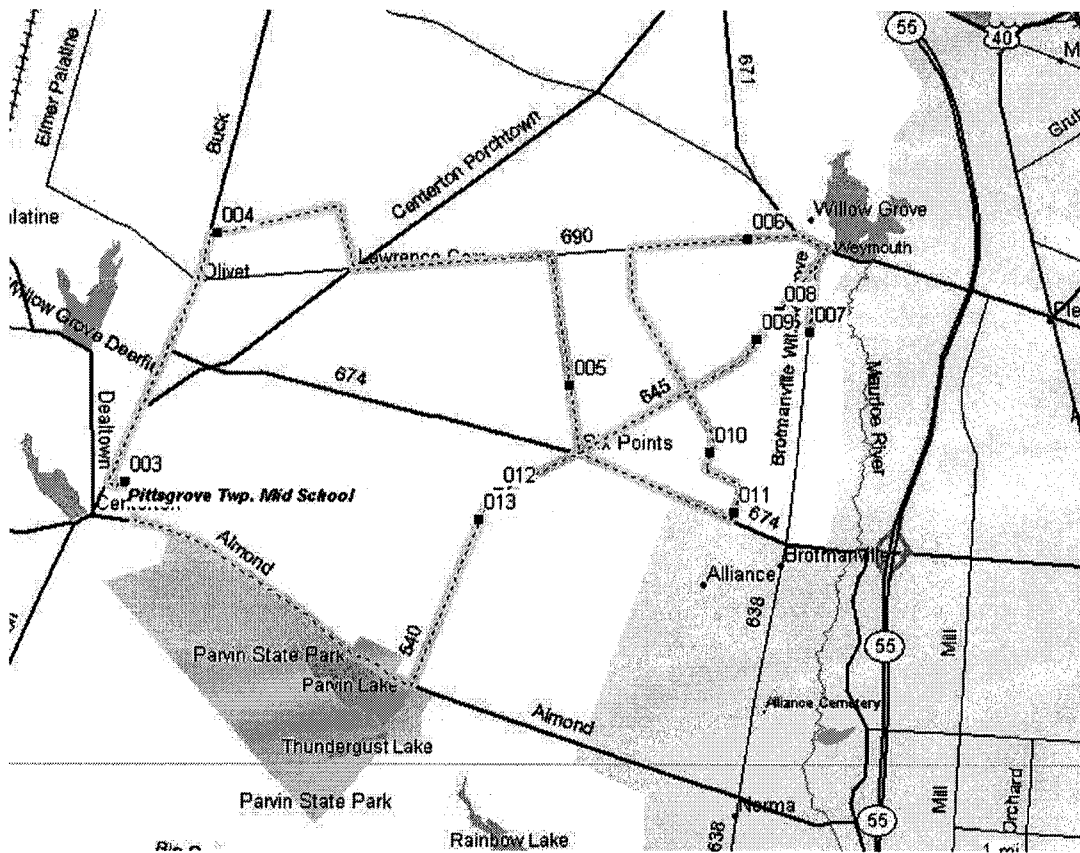


Figure 23: Pittsgrove Township GPS Map

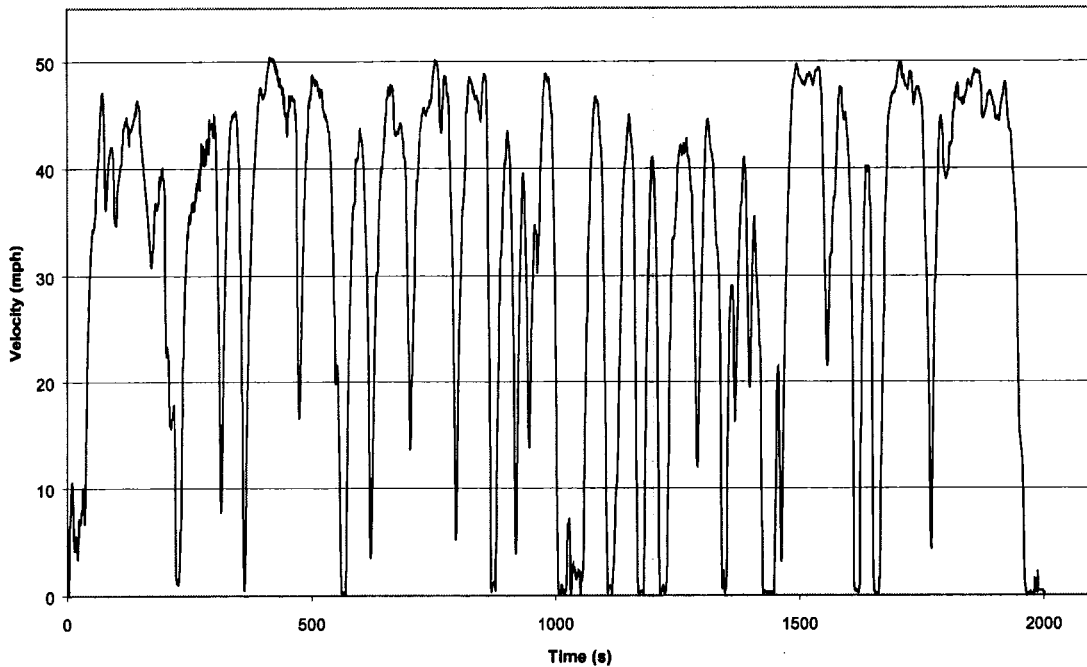


Figure 24: Pittsgrove School District velocity vs. time profile

3.3.3. Data Reduction/Cycle Development

Statistical information from the GPS data was first calculated for each microtrip. The following metrics were calculated for each microtrip for further data analysis:

- maximum microtrip velocity (mph)
- average velocity (mph)
- standard deviation of velocity
- total time (s)
- total distance (miles)
- percent idle (%)

The same statistical calculations were performed on all 135 individual microtrips and averaged over all of the microtrips within each of the three categories. Table 7 provides statistical information on the microtrip characteristics of urban (A), suburban (B), and

rural (C) areas, respectively. As mentioned previously, urban areas have the lowest mean speed, the shortest length of a microtrip in time and distance, and the longest average idle time (more students at each stop). Rural areas generally tend to have more pick-up stops and only one or few students to pick up at each stop. The total numbers of microtrips in each category were 71, 57, and 7 for categories A, B, and C respectively.

Table 7: Statistical Information on Microtrip Categories

Microtrip Category	Mean Speed (mph)	Average Time (seconds)	Mean Distance (miles)	Average Idle Time (%)
Urban (A)	12.7	65.9	0.2	22.5
Suburban (B)	28.7	130.5	1.1	8.0
Rural (C)	38.3	192.0	2.1	3.6

One final check to make sure that the categorical separation makes sense was to look at specific bus trips. Washington Township and Glassboro were considered the most urban of the areas tested. All trips from these areas were made up primarily of category A microtrips. The Pittsgrove runs were considered the most rural and were composed mostly of microtrips from categories B and C, containing only a few microtrips from category A. The Medford and Deptford trips were a mixture of microtrip types and are classified as suburban.

Once the microtrips were separated into categories, the most representative microtrips in each category were chosen. The most representative of the microtrips were those that had the closest relationship between the average speed, standard deviation of velocity, and % idle as compared to that of the total values for each category. To determine the closest microtrips, a root mean squared calculation (performed using MATLAB) with these parameters, equally weighted, was performed. The root mean squared equation

used to determine the closest microtrips is as follows:

$$rms = \sqrt{(V_T - V_{m_i})^2 + (Std_T - Std_{m_i})^2 + (\%I_T - \%I_{m_i})^2} \quad 8$$

where V_T is the mean velocity, Std_T the standard deviation of velocity and $\%I_T$ the percent idle time of all of the microtrips in a certain category. The terms V_{m_i} , Std_{m_i} , and $\%I_{m_i}$ are the mean velocity, standard deviation of velocity, and percent idle time of each individual microtrip from a certain category, respectively. Accelerations, decelerations, and cruise time were not considered in the determination of the most representative cycle due to the time lag that is associated with the GPS device.

Once each representative microtrip was selected, its empirical cumulative distribution function (ECDF) was graphed and compared to the total ECDF for all microtrips to ensure that they passed a visual inspection and that they followed similar trends. The “ECDF” was plotted using the Matlab statistical toolbox.

To construct the most representative cycle, parameters such as time length, number of each type of microtrip, and duration of end idle needed to be determined. A minimum length of 20 minutes was chosen because it was within the range of the length of the bus trips analyzed and could be comfortably executed by a driver at ATC. To determine the number of microtrips to use from each category, the percentage of the total time of all trips that each type of microtrip and idle period composed was calculated. The representative cycle was then developed with similar time proportions.

The representative microtrips were concatenated until these desired parameters were fulfilled. The composite cycle was obtained by choosing the 6 most representative category A microtrips, the 6 most representative category B microtrips, and the one most representative category C microtrip. Once the microtrips were pieced together, an

average idle was added to the end of the representative cycle consisting of 47 seconds, which was the average duration of “end of run” idle time for all of the 11 bus routes. The total duration of the RUCSBC cycle is 1241 seconds. See Table 8 for a breakdown of category percentages pertaining to the desired time length of each category and the actual length of each category in the RUCSBC.

Table 8: Microtrip Times for a Cycle with a Minimum of 20 Minutes

Microtrip Category	Time Desired (seconds)	Time Obtained (seconds)	% Difference
A	400.9	445	8.8
B	636.8	658	1.31
C	115.0	74	36.9
Idle Time	47.3	47	2.66

To ensure that the cycle was easy for a driver to follow and perform, an additional idle period (10 seconds) was added at the beginning of the cycle and all of the idle periods were zeroed (the GPS has an accuracy of 2mph). The velocity vs. time profile of the RUCSBC can be seen in Figure 25. The RUCSBC (velocity vs. time) is also shown in Figure 26 broken down into the three-microtrip categories urban (A), suburban (B), and rural (C).

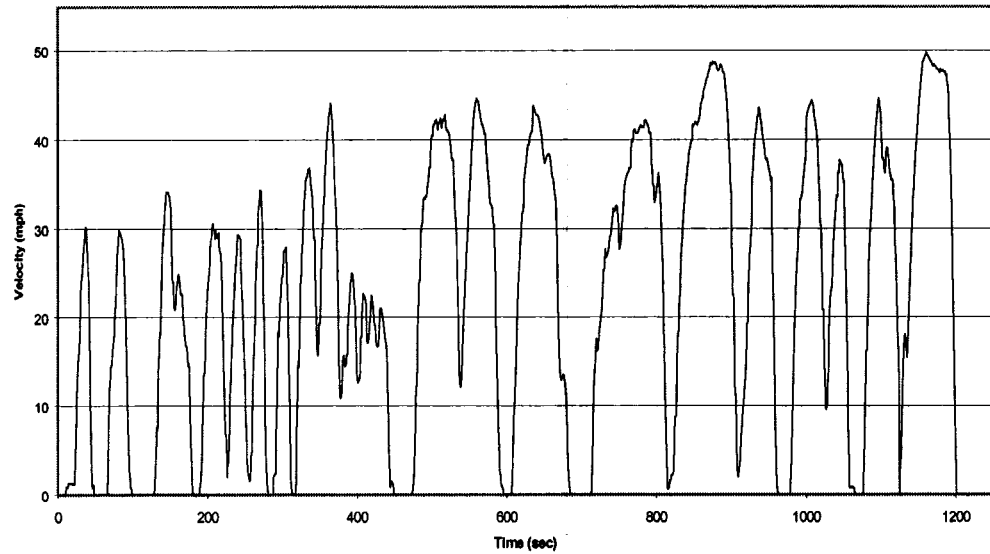


Figure 25: The Rowan University Composite School Bus Cycle

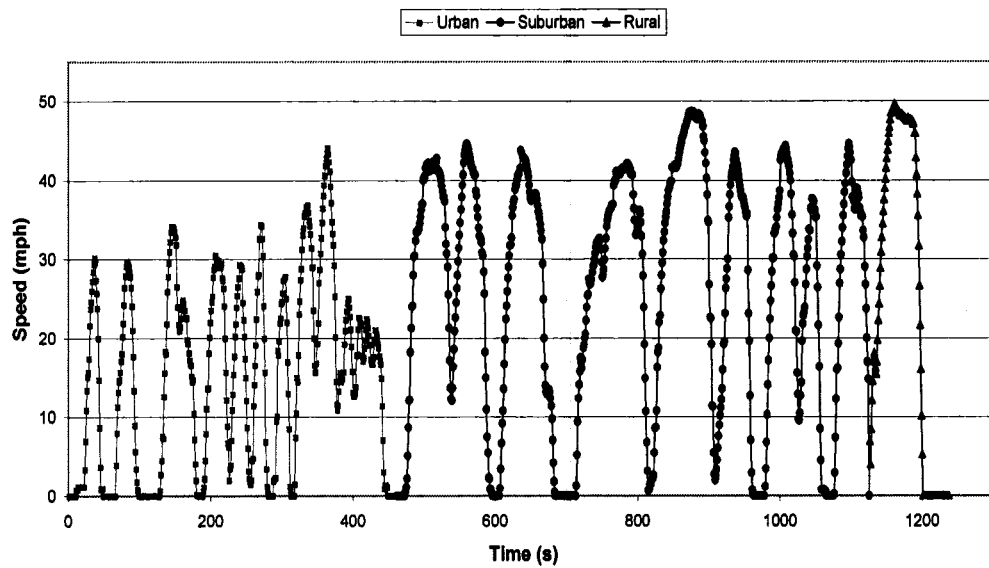


Figure 26: Rowan University Cycle Separated by Representative Regions

A visual inspection of the cycle illustrates an apparent distinction between the urban, suburban, and rural components. Finally, because prior mobile test cycles created and tested by Rowan using GPS data contained some considerably harsh accelerations and decelerations (due to GPS lags), the velocity gradient of the RUCSBC was graphed

(using Matlab) and inspected. The areas with high accelerations and decelerations were manually smoothed such that the maximum value was adjusted from approximately 10mph/s to 7mph/s. This adjustment allowed the driver to follow the Semtech trace provided by the ECM more smoothly and accurately.

An initial driving test of the cycle was performed successfully at the ATC 1-mile loop. During the driving test it was shown that the same driver could execute the cycle with adequate repeatability. The close repeatability of the driver following the Semtech speed trace is shown in Figure 27, and again in Figure 28, which is a speed vs. time trace of the RUCSBC driven on the 1-mile loop by the same driver using the DT466 bus. The processed data also showed close comparison between the same two runs with respect measured emissions, further proving the cycle's repeatability. Figure 29 and Figure 30 show the instantaneous NO_x concentration measured during the two runs shown in Figure 27 and Figure 28. From Figure 29 and Figure 30 it is evident that during the idle periods of the RUCSBC the NO_x levels always returned to the same concentration and peaked at similar positions during the cycle. From the emission and GPS data it was concluded that the RUCSBC is a repeatable cycle when executed at conditions of similar temperature and absolute humidity.

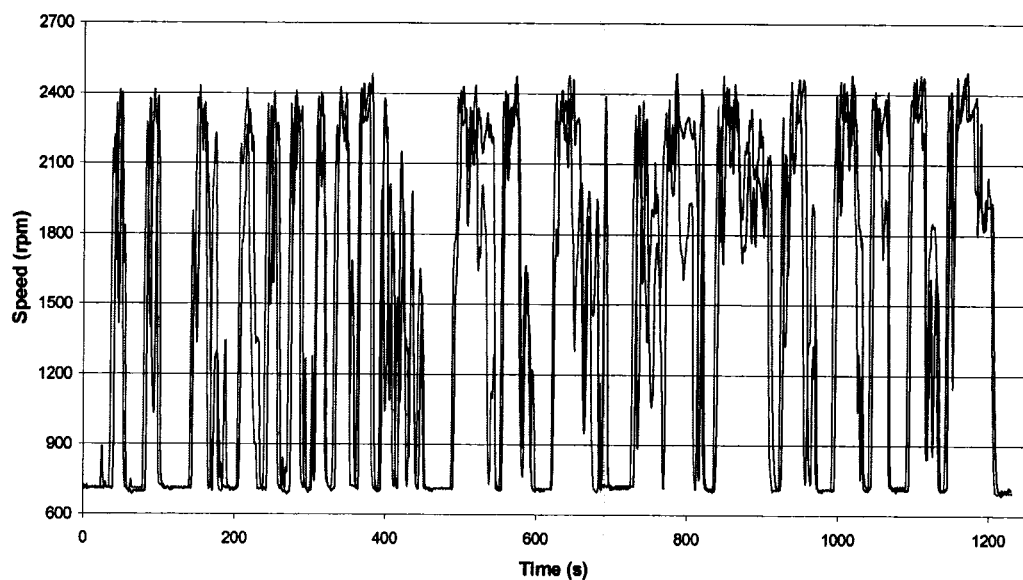


Figure 27: Speed Trace of Two Separate Runs of the RUCSBC

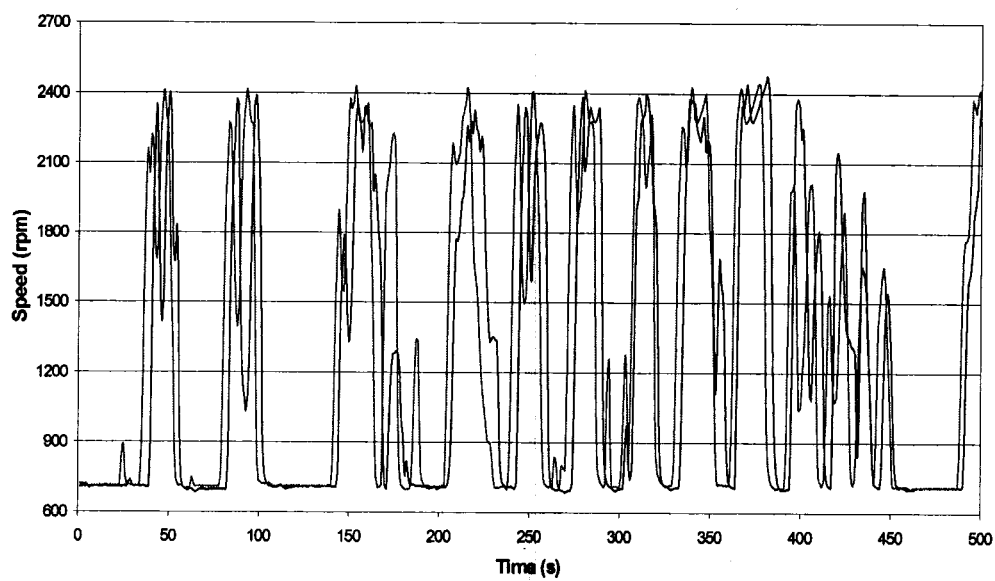


Figure 28: Speed Trace of Two Separate Runs of the RUCSBC (Reduced Axis)

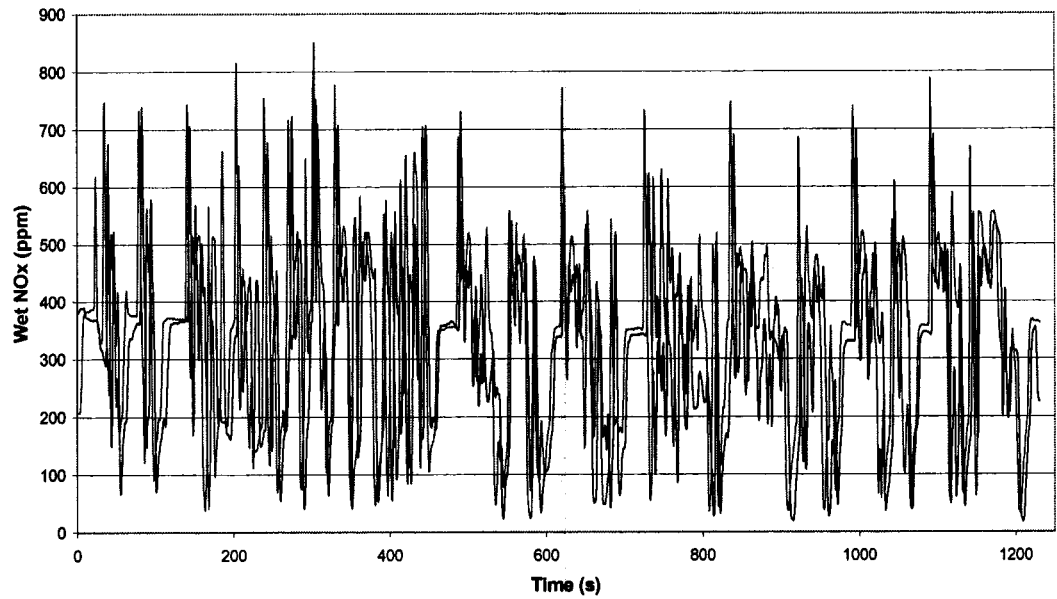


Figure 29: NO_x Concentration Trace of Two Separate Runs of the RUCSBC

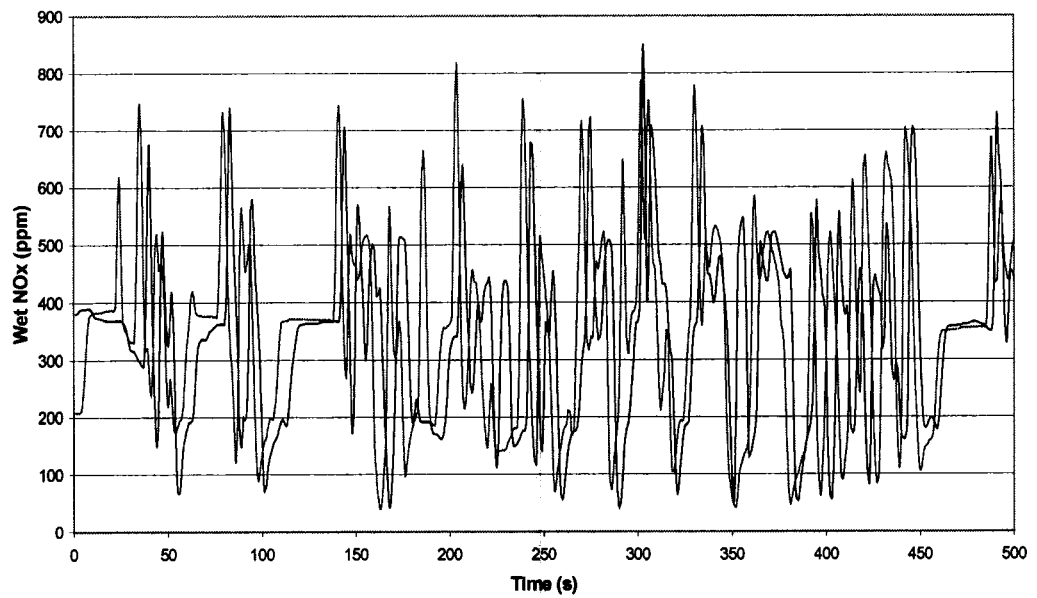


Figure 30: NO_x Concentration Trace of Two Separate Runs of the RUCSBC (Reduced Axis)

4. Rowan On Road Medford Township School Bus Testing

4.1. Introduction

This chapter provides emissions data taken from school buses in the Medford Township School District running on #2 diesel and biodiesel. In conjunction with the school bus emissions reduction study being performed at ATC, Rowan University performed emissions testing at a local school district already running biodiesel. Since a local school district (Medford, NJ) currently employs a B20 biodiesel blend to fuel 50% of their fleet, actual on-road emissions data were acquired in addition to the tests performed on the test track at ATC. The on-road tests were performed at the Medford Township School District in Medford, NJ on four of the districts 44 buses. Over the past five years, Medford has converted half of their 44-bus fleet to a blend of 20 percent biodiesel and 80 percent petroleum (B20) purchased from World Energy Alternatives. Since converting Medford has had no known problems with running biodiesel even at temperatures of 11 degrees below zero³⁶.

4.2. Purpose of Medford Study

In recent emission reduction programs for heavy-duty diesel engines, biodiesel has become a popular alternative fuel for testing. In an effort to acquire as much emissions data as possible, Rowan tested at the only school district in NJ and the surrounding area running school buses on any mixture of biodiesel. Tests were performed in Medford in the month of January on two separate occasions. Since 1997, Medford has run biodiesel in almost half of their buses, but they had never had them tested for emissions to see if their efforts in running on biodiesel were worthwhile. Rowan was able to provide Medford with emissions data that could only otherwise be acquired by purchasing or

renting expensive testing equipment. Medford was able to provide Rowan with buses that have been running on biodiesel for many years, which is in contrast to results presented in Chapter 6, which present the immediate results of switching from one fuel to the next.

4.3. Medford School District Biodiesel Program

Medford Township, located in mainly rural Burlington County in central New Jersey, received a grant in 1997 to convert half of the fuel used in their school bus fleet of 44 buses (which can be seen in Figure 31) to a B20 mixture of biodiesel. The U.S. Department of Energy provided the New Jersey Board of Public Utilities, Division of Energy \$115,000 for the project under a 1997 grant. Since 1997, Medford school buses have logged over 400,000 miles on buses operated by biodiesel. Medford school district director of operations and technologies Joe Biluck, Jr. spearheaded the movement to biodiesel in the districts buses. Biluck has noticed only positive results since switching,

"We've had no down time as a result of this fuel. We've seen no drop in miles per gallon, which means the engines aren't working any harder." "We've never had a fuel system gel up on us," Biluck said. "We've run down to temperatures of 11 degrees below zero and haven't experienced any problems."³⁶

Medford Township School District is the oldest account held by biodiesel supplier World Energy Alternatives. The only added costs for Medford in running with biodiesel has been the slightly higher cost for the fuel (~\$0.15) and the addition of a biodiesel storage tank, which is shown in Figure 32.



Figure 31: Medford Township's biodiesel operated school bus fleet

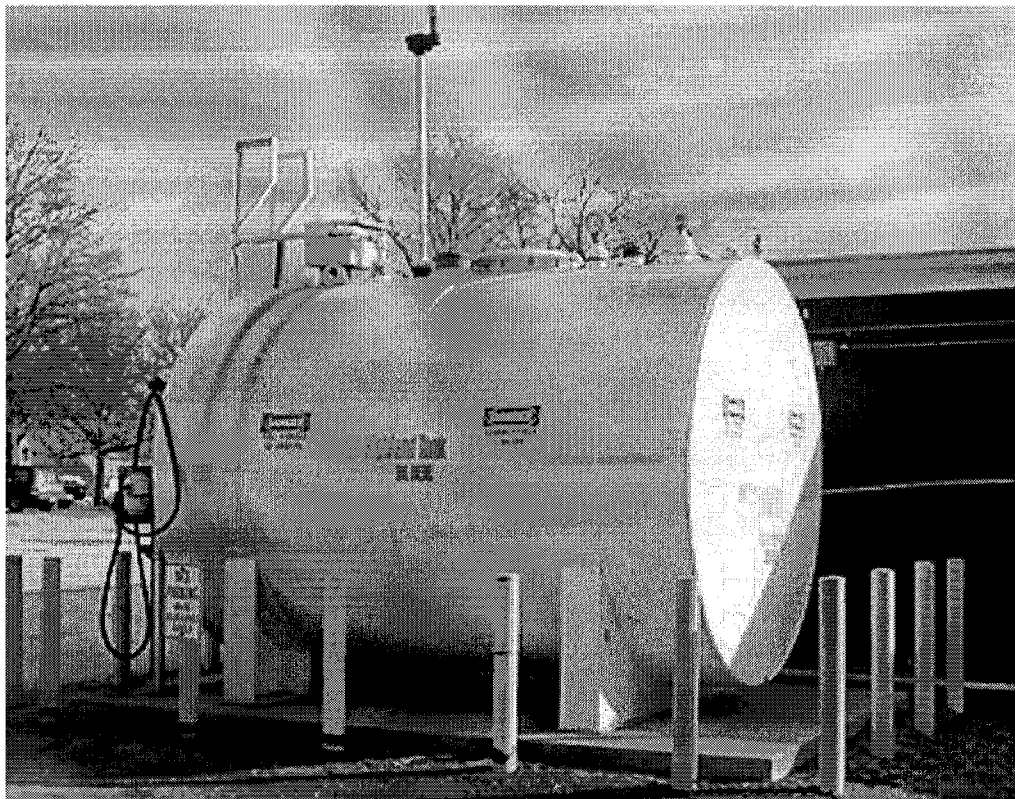


Figure 32: Medford biodiesel storage tank

4.4. Experimental Setup: Test Procedure

All four buses tested in Medford used International DT466 engines. The specifications of the school buses tested can be seen in Table 9. Buses 76 and 80 have been operated using B20 fuel for four years while Bus 84 has been operating for only one year. Bus 77 has been operating entirely on #2 petroleum diesel, since it was put into the Medford school bus fleet in 1998. The 2002 and 1998 DT466 series engines were similar in all aspects (displacement, power, etc.) except total number of miles (about $\frac{1}{4}$ of the miles on Buses 76, 77, and 80). The same school bus route was performed twice on each school bus using the Semtech-D and Garmin GPS equipment to measure the vehicle parameters and emissions. Note that the Medford cycle was used as one of the 11 cycles to create the RUCSBC.

Table 9: Vehicle and engine data for Medford school buses investigated.

Medford Bus #	Engine	Fuel
76	'98 International DT466	B20
77	'98 International DT466	#2 Petroleum Diesel
80	'98 International DT466	B20
84	'02 International DT466	B20

The Medford school bus route shown in Figure 33 is approximately 8.25 miles in length and has a duration of approximately 25 minutes. The tests were performed in January at the same approximate temperature of 35 °F and absolute humidity of 9 grains/lb.-dry air. The same driver was used for all Medford school bus data collected. All of the bus routes had approximately the same average engine and vehicle speeds of 1480 rpm and 20 mph, respectively.

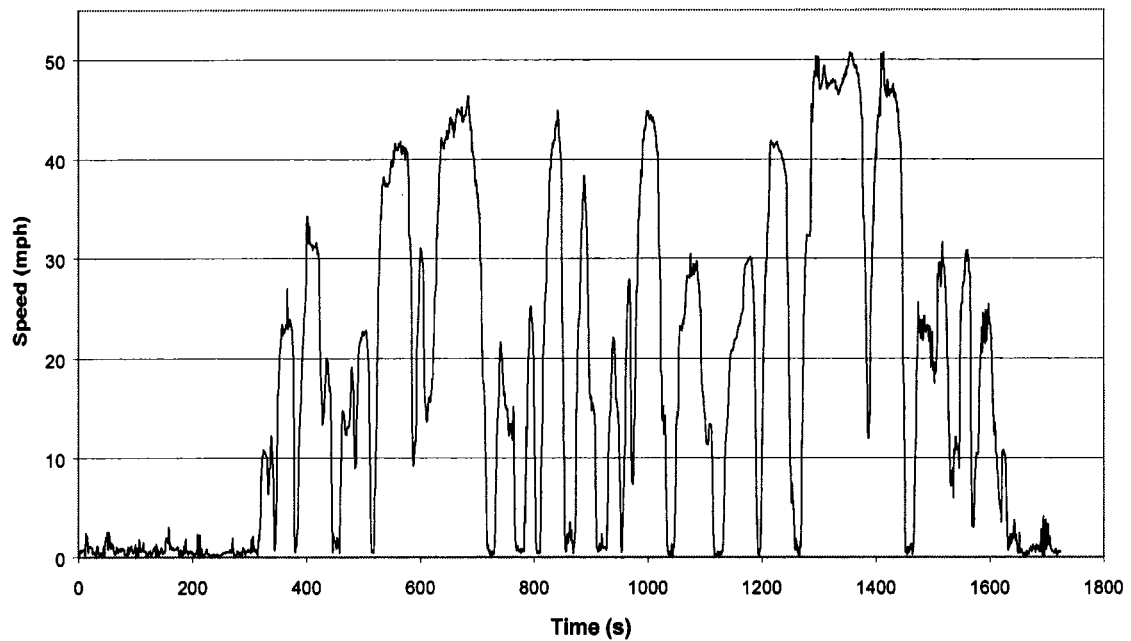


Figure 33: Speed Trace of Simulated Medford School Bus Route

4.5. Test Results

4.5.1. Medford Fuel Consumption/Total Work

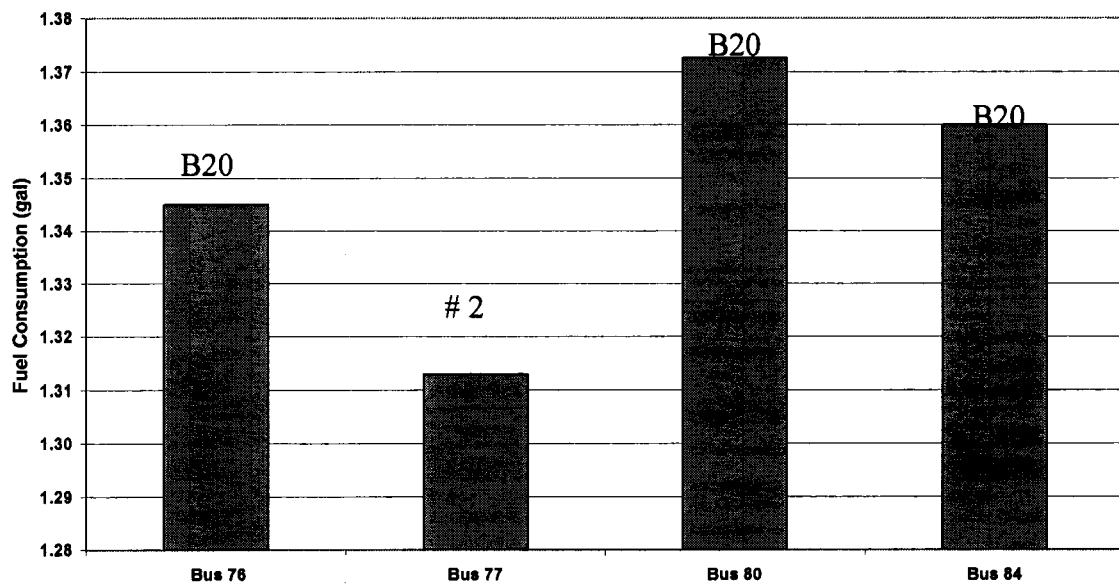


Figure 34: Fuel Consumption for Medford school buses tested

As described in Chapter 2, Semtech-D relies on the ECM to provide fuel flow information in order to calculate fuel flow rate and time specific mass emissions. The ECM determines the fuel flow rate based on the real-time pulse width of the fuel injectors.⁵⁴ The total fuel consumption is then calculated instantaneously from the volumetric fuel flow rate and fuel density, which is supplied by the user. There was no fuel analysis completed on the Medford fuels so the standard value of $.85 \text{ g/cm}^3$ was used for fuel density of # 2 petroleum diesel and $.86 \text{ g/cm}^3$ was used for B20 (estimated based on B20 used for ATC Fuels test described in Chapter 6).

Biodiesel is expected to increase fuel consumption due to its 8 % lower calorific value by volume when compared to conventional diesel.³⁵ Previous studies have found that a B20 blend produced a 1.6% reduction in fuel economy when the biodiesel was produced from soybeans or rapeseeds.³⁵ Figure 34 shows that for all Medford buses tested operating on a B20 blend there was an increase in fuel consumption. The B20 fueled buses increased fuel consumption slightly 2.4 % for Bus 76, 4.5 % for Bus 80, and 3.6% for Bus 84.

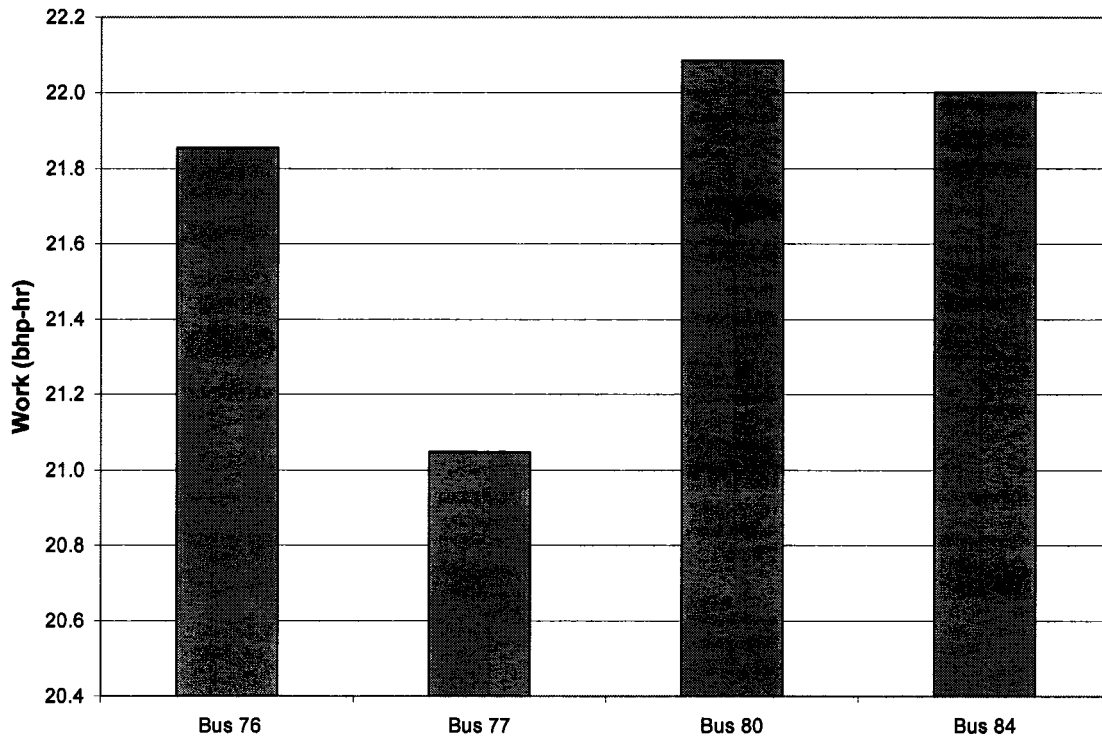


Figure 35: Work for Medford school buses tested

The engine torque is computed by Semtech-D using the engine's known lug curve and vehicle parameters such as engine speed and % load. The torque is then used to calculate the total work done by the engine for each second of the test and integrated over the total time of the test. Figure 35 shows the total work for the Medford school buses tested. Variations in traffic patterns may account for the variations in total work for the same route. As shown in Figure 36, fuel consumption is proportional to the total work the engine undergoes to complete the cycle. The same driver using the same route performed the Medford school bus emission runs. However, the tests were not run under controlled conditions, so factors such as stop lights and pedestrian traffic influenced the consistency of the runs and thus may have affected the work and fuel consumption. The experimental values for fuel consumption and work can be seen in Table 10.

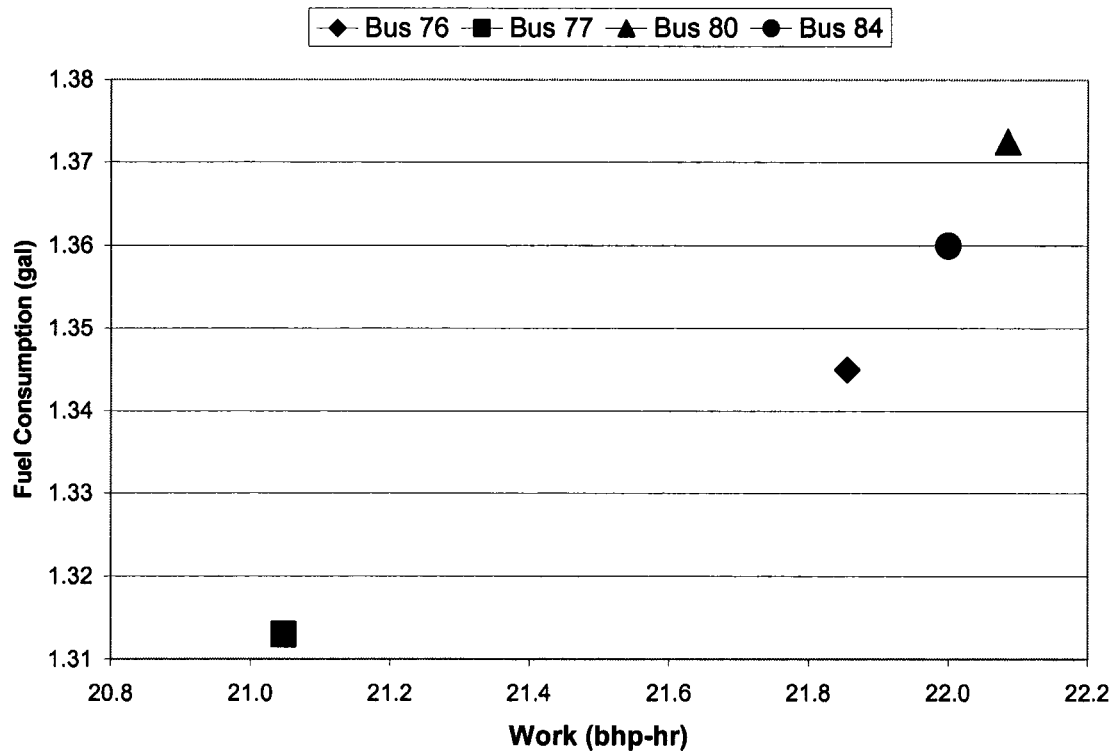


Figure 36: Fuel Consumption as a function of work for Medford school buses tested

Table 10: Medford fuel consumption and work

Bus #	Fuel Consumption (gal)	Total Work (bhp-hr)
Bus 76	1.35	21.9
Bus 77	1.31	21.0
Bus 80	1.37	22.1
Bus 84	1.36	22.0

4.5.2. Medford Emissions

Figure 37 shows a representative breakdown of all emissions data collected in Medford from the Semtech-D unit. As shown in Figure 37, the buses operated on B20 produced slightly higher CO₂ emissions levels and lower CO, NO_x, and HC emissions

then the bus powered on the #2 conventional petroleum diesel.

Bus 84 had only operated on B20 for approximately one year prior to the tests conducted for this study, while the other two buses had operated on B20 for almost four years. The same driver tested all four buses under similar conditions (ambient temperature and humidity) under the same route. Similarities in vehicle (% load, oil temperature, and engine and vehicle speed) and testing conditions parameters are shown in Table 11. From the data provided in Table 11, it is concluded that Medford testing was repeatable and can be justly compared. Average Medford school bus emission values are quantified in Table 12 and Table 13.

Table 11: Vehicle and testing condition parameters for the four different Medford buses tested

Bus #	Load %	Oil Temp. (F)	Ambient Temp. (F)	Absolute Humidity (gr./lb air)	Total Distance (miles)	Engine Speed (rpm)	Vehicle Speed (mph)
Bus 76	36.5	177	32.3	9.9	8.15	1518	20.4
Bus 77	34.7	178	31.9	8.4	8.27	1463	19.9
Bus 80	34.8	180	37.2	10.2	8.36	1429	18.9
Bus 84	35.6	170	35.4	7.6	8.33	1464	19.6

Table 12: Average emissions results for the four different Medford buses tested measured in g/mile

Bus #	CO ₂ (g/mi)	CO (g/mi)	NO _x (g/mi)	kNO _x (g/mi)	HC (g/mi)
Bus 76	1708	1.78	12.14	12.02	0.69
Bus 77	1574	1.89	13.97	13.36	0.95
Bus 80	1690	1.54	13.27	12.71	0.88
Bus 84	1650	1.78	13.84	13.01	0.87

Table 13: Average emissions results for the four different Medford buses tested measured

in g/bhp-hr and ppm concentration

Bus #	Wet NO _x (PPM)	kNO _x (PPM)	Wet HC (PPM)	CO ₂ (g/bhp-hr)	CO (g/bhp-hr)	NO _x (g/bhp-hr)	kNO _x (g/bhp-hr)	HC (g/bhp-hr)
Bus 76	316	270	55	637	0.69	5.23	4.48	0.26
Bus 77	368	314	81	616	0.77	6.13	5.22	0.37
Bus 80	325	278	73	640	0.59	5.63	4.81	0.33
Bus 84	348	297	71	622	0.67	5.46	4.77	0.33

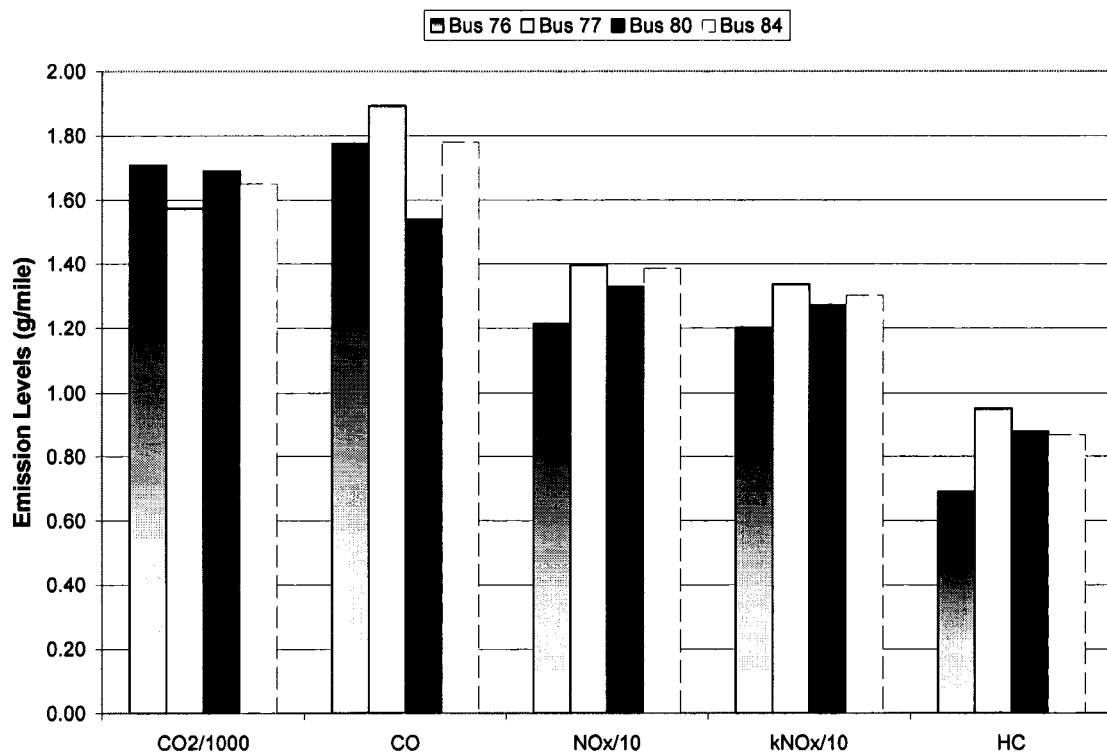


Figure 37: Average emissions results for the 4 different Medford buses tested.

As stated previously, the EPA concluded (from a variety of previous studies performed mainly on engines dated before 1997) that, on average, B20 reduced HC emissions by 20%, PM emissions by 10%, and CO emissions by 11%. NO_x emissions increased slightly in some engines (~ 2%) and CO₂ emissions showed little or no

difference.³⁵ In the present study, HC emissions showed some significant reductions with the use of B20, particularly in Buses 76, which showed a reduction of 27.2 % when compared to the baseline #2 diesel bus (Bus 77). These reductions are higher than those found by the EPA cumulative study. However, Bus 80 and Bus 84 reduced HC emissions by only 7.4 % and 8.4 %, respectively, which was slightly lower than given by the study. CO emissions were slightly decreased by 6.1 % and 5.9 % with the use of B20 in Buses 76 and 84, respectively, when compared to the baseline #2 diesel bus (Bus 77). Bus 80 showed a much higher CO decrease than the other buses of 18.7 %. These decreases in CO emissions were expected since the EPA report claimed that B20 was expected to slightly reduce CO emissions.

NO_x emissions showed slight reductions between 1.0 % and 13 % with the use of B20. Semech's corrected NO_x (kNO_x) also slight reductions between 2.6 % and 10 %. An SAE NO_x correction factor for temperature and humidity was not used for the Medford data because all tests were conducted within a close range of 5 °F and 2 gr./lb-dry air, respectively. Previous work has found however, that NO_x emissions generally increase slightly with biodiesel.^{32, 35} The NO_x increases when using biodiesel could be caused by the higher fuel density and lower heating value of the fuel.³² Increasing oxygen content in the fuel has caused significant increases in NO_x in previous research.³² The NO_x tradeoff is not a large concern however, due to the low sulfur content of biodiesel (~24 ppm), which will work with NO_x reducing technologies that require low sulfur fuel.

The slight reduction of NO_x emissions from the Medford biodiesel buses could be a result of the B20 being mixed with kerosene for winterization. It is a common practice

for cold weather areas to mix kerosene with biodiesel to lower the cloud point of the fuel to prevent gelling. Kerosene has a lower relative density ($\sim 0.80 \text{ g/cm}^3$) when compared to B20 ($\sim 0.86 \text{ g/cm}^3$) and #2 petroleum diesel ($\sim 0.85 \text{ g/cm}^3$). Kerosene also contains a slightly higher heating value (20,000 btu/lb) when compared to biodiesel (17,500 btu/lb). A previous study on the effect of kerosene in #2 petroleum diesel fuel found that the addition of kerosene slightly reduces NO_x and PM emissions and slightly raises CO and HC emissions.⁶⁴

The Medford data concurred with the EPA study that there was little change in CO_2 emissions (between 2.4 % and 4.5 %) from using B20. However, the real savings in CO_2 emissions comes from the fact that biodiesel is renewable, meaning the CO_2 emission released into the atmosphere when biodiesel is burned is recycled by growing plants, which are later processed into fuel. A small percentage of tailpipe fossil CO_2 produced from operating on biodiesel can be attributed to the methanol contribution, however almost 95 % of the biodiesel created CO_2 emission is tailpipe biomass CO_2 .⁶⁵ A recent government study shows that the use of biodiesel can reduce CO_2 emissions by 78.45% on a life cycle basis, which include emissions in the production of the fuel.⁶⁵

5. School Bus Idle Emissions

5.1. Introduction

In addition to implementing reduction technologies for mobile emissions from school buses, NJDOT has also identified the reduction or elimination of school bus idling as a potential component of future SIP's. There are approximately 11,000 school buses used each day in the state of New Jersey.⁴⁷ These school buses are often idled in the morning prior to their initial bus route and in the afternoon while waiting to pick up the children to take them home. School bus idling occurs for the following reasons:

- to keep the engine and fuel warm in cold weather,
- provide heat inside the bus in cold weather and,
- to provide power for lighting for safety purposes.

Heavy Duty Diesel Vehicle (HDDV) truck engine idling results in costly fuel consumption and engine wear. Moreover, idling produces pollutants in the form of nitrous oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons (HC), and particulate matter (PM), which may be avoidable with the reduction of unnecessary idling. Indeed, unlike mobile emissions, which can at best be reduced through a variety of costly technologies, idle emissions can be completely eliminated by eliminating unnecessary idling.

School bus idle experiments were conducted at the United States Army Aberdeen Test Center (ATC) in Aberdeen, Maryland. In the experiments described herein, three school buses were tested in an environmental chamber where the ambient temperatures of 20°F, 40°F, 65°F, and 85°F and relative humidity were held constant. The objectives of this study were as follows:

- quantify fuel consumption rates of school buses at idle,
- quantify school bus idle exhaust emissions at various temperatures and humidity's,
- determine the effects of ambient temperature and humidity on school bus engine idle emissions and fuel consumption, and
- create engine specific NO_x correction factors for each school bus engine presently undergoing mobile emissions reduction technologies testing in a parallel study.

5.2. Literature Search

5.2.1. HDDV Study

Previous idle emission studies on HDDV's have mainly been performed on heavy-duty trucks. A significant fraction of diesel emissions can be attributed to HDDV's at idle conditions during which power is being used for systems such as cabin heating or cooling. In the spring of 2002, the U.S. Environmental Protection Agency, in collaboration with the New Jersey Department of Transportation, the U.S. Army Aberdeen Test Center, Oak Ridge National Laboratory and Rowan University initiated a study to quantify the idling emissions and fuel consumption rates for HDDV trucks. Testing was performed in an environmental chamber at ATC on five different class 8 trucks with model years ranging from 1990's to 2001. To simulate a wide variety of idling situations, 38 tests were conducted at three different ambient temperatures (0°F, 65°F and 90°F), relative humidity ranging from 22 to 90% and idle speeds from 600 to 1200 RPM. Each test was conducted for approximately three hours during which HC, NO_x, CO, CO₂, O₂, and PM emissions were monitored.

The test results show that the emission rates are a function of both the inlet

temperature and engine load. For example, a Detroit Diesel engine idling at 600 RPM produced an average NO_x emission of 54.8 g/hr for 0° F ambient temperature (with cabin heater activated) to 105 g/hr at 90° F (with cabin air conditioner activated). The effect of humidity was evidenced through a 15 to 20% decrease in NO_x concentration when relative humidity increased by a factor of three. However, the HDDV vehicles have engines that are almost double the displacement of school bus engines. Therefore, these values cannot be used to accurately estimate the emissions and fuel consumption from school bus idling. Moreover, most school buses are not equipped with air conditioning units, nor does a school bus have to power any appliances and/or refrigerate or heat cargo.

The results from the HDDV truck idling study also show that ambient temperature and humidity can have a significant effect on the formation of NO_x gases.⁶⁶ Accordingly, the present idle study was performed to accurately quantify emissions from school bus idling for various temperature and humidity.

The present school bus idle emissions study is also an integral part of larger study involving the characterization of emission reduction strategies using a mobile testing procedure. As described in detail in Chapter 6 of this thesis, since the mobile emissions testing is performed outdoors on a test track, the inlet air temperature and humidity is not controlled. It is also well documented that NO_x emissions are a strong function of temperature and humidity.⁵⁵ In order to eliminate the difference in NO_x emissions created by ambient temperature and humidity, correction factors are applied to the NO_x data. Therefore, in order to compare the effects of various emission reduction strategies and alternative fuels, an accurate correction factor for NO_x emissions needed to be developed.

5.2.2. School Bus Idling

The California Air Resources Board (CARB) conducted the only known study on school bus idling. The study, titled “Airborne Toxic Control Measure to Limit School Bus Idling and Idling at Schools,” examines the estimated health effects from school bus idle emissions in California.⁶⁷ The study provides estimated idle emission values from HDDV’s and states that school bus idle emissions should be similar, but never measured any actual idle emissions. The study also analyzes the effects of other diesel vehicles (e.g. food delivery trucks, garbage trucks, official school use utility trucks, etc.) that might be present on or around school grounds. The research herein provides measured emissions and fuel consumption rates from various school buses operating under a variety of controlled temperature and humidity conditions.

5.3. Experimental Procedure: Test Matrix

Three school buses were tested at the Aberdeen Test Center (ATC) in Aberdeen, Maryland inside an environmental chamber. The environmental chamber is capable of controlling multiple climatic variables, including temperature, humidity, solar radiation, dust, icing, fog, and thermal shock.⁶⁸ The full climatic chamber dimensions are 75 ft x 40 ft x 24 ft, however only half of the chamber was used for this testing. In order to simulate the range of humidity over the four temperatures, 33 tests were performed. Engine data for each of the school buses utilized in the testing are shown in Table 4.

The test matrix of temperatures and corresponding humidity shown in Table 14 were chosen based on typical temperatures seen by a New Jersey school bus during the course of a school year. The test matrix was performed one time on each bus tested. The 85° F and 40 % relative humidity (~ 75 grains/lb. dry air absolute humidity) is the current

standard condition for stationary emissions testing to correct for NO_x and all other data points collected will be corrected to that value.^{55,69}

Table 14: Environmental test matrix for each bus

Test	Temperature °F	Relative Humidity %
1	20	65
2	40	40
3	40	65
4	40	90
5	65	40
6	65	65
7	65	90
8	85	40
9	85	65
10	85	90

The Sensors Inc. SEMTECH-D mobile emissions analyzer and the Sensors Inc. PM-300 particulate measuring device were used to acquire the exhaust constituents of CO, CO₂, NO, NO₂, HC, and PM during each test.

Each test was approximately one hour in length. During this period, the temperature and humidity were held constant in the environmental chamber. After 1 hour, the time rate of change of the oil temperature was generally 0.2°F per minute for the last 10 minutes. Steady state values of emission levels and fuel consumption were obtained by computing time averages over the final 10 min. Figure 38 is an example of the NO_x emissions and oil temperature from a typical test conducted on the DT466E bus at 40°F and 40% relative humidity. Figure 38 shows that the measured NO_x emissions vary as the engine warms up. The higher NO_x emissions during the transient startup period are a result of increased engine load as evidenced by the increased fuel flow rate during this same period. The increased engine load during the transient period is a result of

increased engine oil viscosity and battery charging requirements.

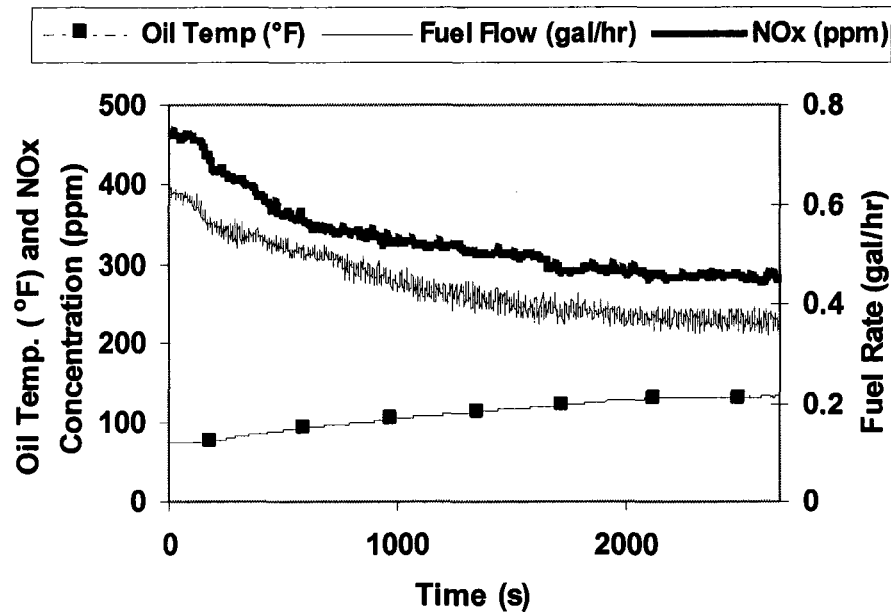


Figure 38: Typical NO_x emissions during a test

Based on Figure 38 above, it is possible that the entire engine system is not completely at steady state after approximately 1 hour of idle operation. For example, the oil temperature is still slowly increasing. However, because of time and cost constraints associated with the use of the environmental chamber at ATC, tests were limited to one hour. To determine the error in emissions measurements associated with truncating the experiments at one hour, analytical expressions were fit to the data to extrapolate the emissions values that would likely have been measured had the experiments been conducted for longer time periods. The results generally showed that had the tests been conducted for an additional 30 minutes, NO_x concentrations would only have been reduced by a maximum of approximately 10 ppm.

5.4. Test Results

5.4.1. Fuel consumption

Fuel consumption at idle for HDDV engines can vary depending on the accessories used.⁶⁶ Most school buses are not equipped with any air conditioning devices, but are equipped with heaters for cold weather. The heater on a school bus contains three fans to evenly distribute heat throughout the school bus. Operating these fans increases the total load on the vehicle's engine and will increase the engine speed at idle. The increase in engine speed in turn raises the fuel consumption. For the experiments reported herein, the heater fans were not turned on. As shown in Figure 39, the fuel consumption rate varies slightly with ambient temperature. The fuel consumption values for the Cummins engine are slightly higher even though the Cummins engine size is 1.4L smaller. In addition, the Cummins engine is not equipped with an ECM and therefore did not adjust fuel injection rates accordingly under various climate changes in the chamber. As shown in Figure 39, the three school buses tested consume an average of 0.5 gallons of fuel per hour.

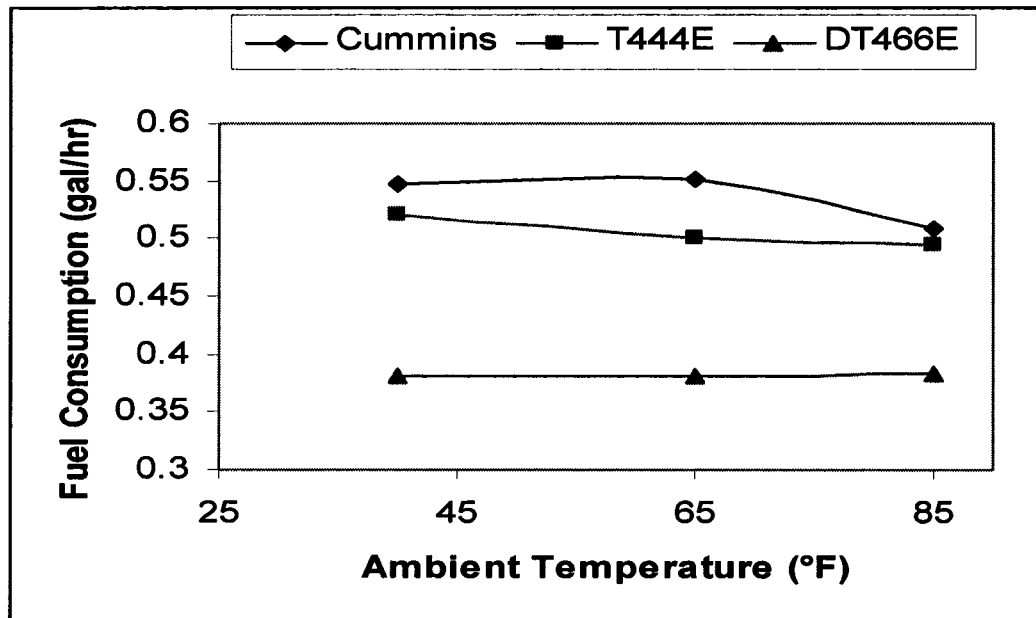


Figure 39: Fuel consumption rates for the three buses tested.

5.4.2. Emissions

Experiments were conducted on each of the three buses over a temperature range of 20 to 85 °F and relative humidity range of 37 to 90 % relative humidity. Measurements of CO, CO₂, NO_x, HC, PM and fuel consumption were made during idling conditions. In all, a total of 33 experiments were conducted. Table 15 contains a summary of all the experimental results.

In addition to the fuel costs associated with idling, exhaust gas contains a variety of chemical species that have adverse effects on human health and the environment. The health risks associated with school bus idling are of a particular concern since much of the idling occurs with children on or near the bus. Particulate matter caused by incomplete combustion is known to contain carcinogens.^{70,71} Also, NO_x, CO and CO₂ are criteria air pollutants responsible for ozone depletion and global warming.

Table 15: Emission results from environmental chamber testing

DT466						
Temperature	Relative	CO₂	CO	NO_x	HC	PM
°F	Humidity %	g/hr	g/hr	g/hr	g/hr	g/hr
20	65	3839	51	74	11.0	0.25
40	40	3801	33	78	11.1	1.88
40	65	3964	36	75	9.2	0.34
40	90	3762	33	75	9.3	1.65
65	40	3825	27	62	11.4	3.18
65	65	3832	26	57	10.4	*
65	90	3783	29	50	11.2	4.10
85	25	3843	21	68	11.2	0.51
85	40	4018	10	64	11.3	*
85	90	3934	36	37	10.4	0.30
T444E						
Temperature	Relative	CO₂	CO	NO_x	HC	PM
°F	Humidity %	g/hr	g/hr	g/hr	g/hr	g/hr
20	50	5417	36	78	8.6	0.34
40	40	5091	22	74	6.8	*
40	60	5104	26	73	10.5	1.61
40	90	5127	29	69	10.1	*
40	40	5180	22	82	7.7	1.09
65	40	5004	25	44	9.0	1.02
65	60	5031	23	54	8.0	1.16
65	90	5296	30	49	8.2	1.03
85	40	5018	21	44	9.7	1.22
80	60	5150	23	38	11.8	0.95
85	90	4998	24	39	10.9	1.21
Cummins						
Temperature	Relative	CO₂	CO	NO_x	HC	PM
°F	Humidity %	g/hr	g/hr	g/hr	g/hr	g/hr
40	50	5323	97	125	25.5	0.33
40	65	5321	103	120	30.7	0.24
40	90	5248	107	115	37.5	0.24
65	90	5053	81	99	37.2	0.20
65	65	5430	78	116	39.1	0.31
65	40	5104	74	117	32.1	0.29
85	40	4916	61	104	36.6	0.22
85	90	4929	54	101	33.2	0.33

* indicates unavailable data

5.4.2.1. CO₂ Emissions

CO₂ emissions are a direct function of fuel consumption. During combustion, the byproducts from the carbon in the fuel are CO, HC, formaldehydes, and CO₂. The majority of the carbon byproducts are formed into CO₂, so as more fuel is consumed, these CO₂ emissions increase almost linearly. Figure 40 is a plot of CO₂ emissions as a function of absolute humidity for all of the temperatures tested for the bus equipped with the DT466E engine. As shown in Figure 40, CO₂ emissions do not demonstrate any type of pattern when temperature and humidity are changed. Similar results were found for the other two buses tested. As the figure suggests, CO₂ emissions for all of the tests conducted in this study averaged approximately 4,700 g/hr.

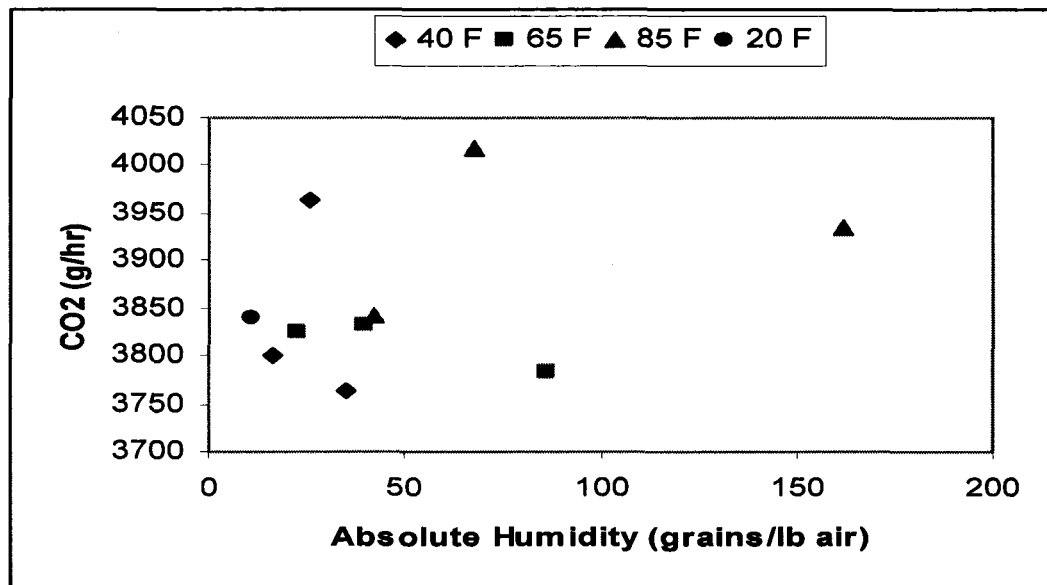


Figure 40: Measured CO₂ emissions during idling for school bus with DT466E engine.

5.4.2.2. CO Emissions

CO emissions are caused by the incomplete combustion of the fuel in the engine. Figure 41 shows the measured effect of ambient temperature on CO emissions of the school buses at idle. As the ambient temperature increases, the cylinder temperature also increases. This increase in cylinder temperature results in a more effective conversion of CO to CO₂, thus more CO₂ is created and in turn less CO is emitted. Since diesel engines generally have excess oxygen and high combustion temperatures, CO emissions are generally much lower than CO₂ emissions. The Cummins engine produced the highest CO emissions by almost double over the newer International T444E and DT466E engines.

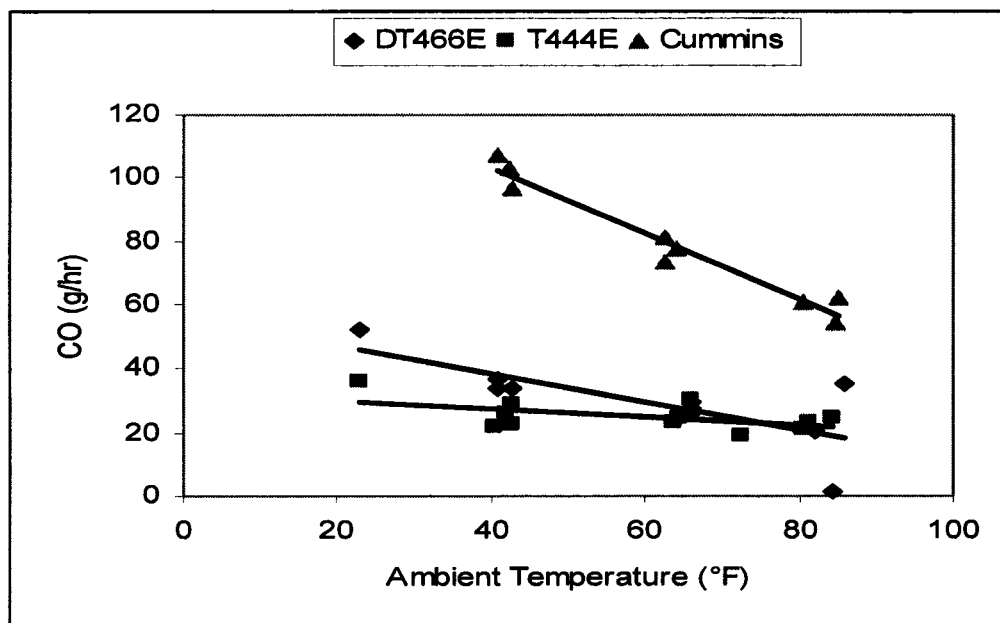


Figure 41: Effect of ambient temperature on CO emissions.

5.4.2.3. NO_x Emissions

Figure 42, Figure 43, and Figure 44 show the NO_x concentration in g/hr from the three buses tested. As shown in the figures, emissions vary not only with temperature and humidity, but also with engine type. The Cummins 5.9L B Series engine produced the highest emissions of the three buses tested. It should be noted that the Cummins engine is the oldest engine tested and does not contain an ECM.

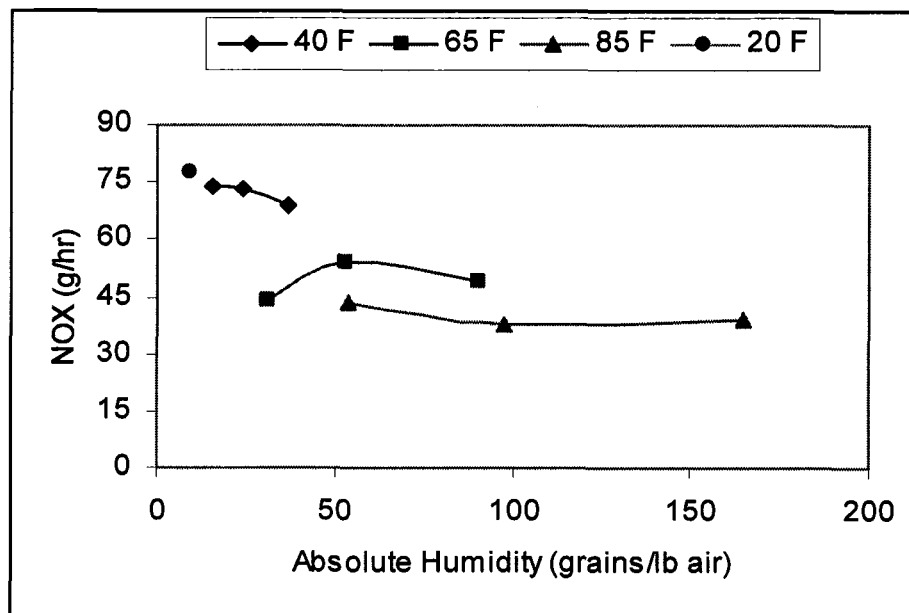


Figure 42: NO_x emissions during idling conditions for school bus with T444E engine.

The NO_x emissions shown above in Figure 42 demonstrate the effect of humidity on NO_x emissions. As expected, the results showed that for each of the buses tested, as humidity increases, NO_x emissions decrease. Since a higher inlet temperature should result in a higher cylinder temperature, it might be expected that NO_x would increase with increasing inlet temperature due to the well-known thermal NO_x mechanism. However, for each of the three buses tested in this study, NO_x emission generally was found to decrease with increasing temperature.

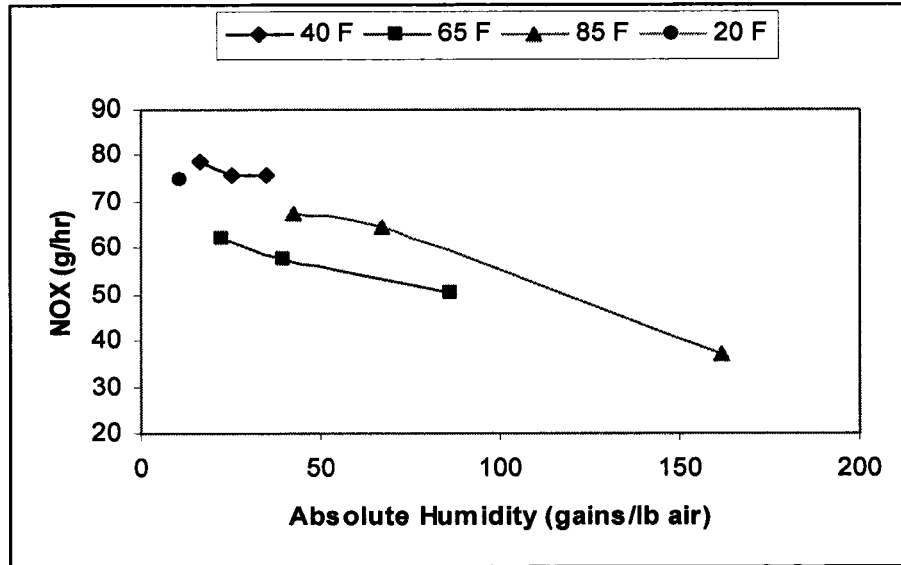


Figure 43: NO_x emissions during idling conditions for school bus with DT466E engine.

Figure 43 also shows a decrease in NO_x emissions as humidity increases. For the DT466E, the measured NO_x emissions were slightly lower than those measured for the T444E engine. The DT466E engine showed a slight increase in NO_x when the ambient temperature was increased from 65 °F to 85 °F.

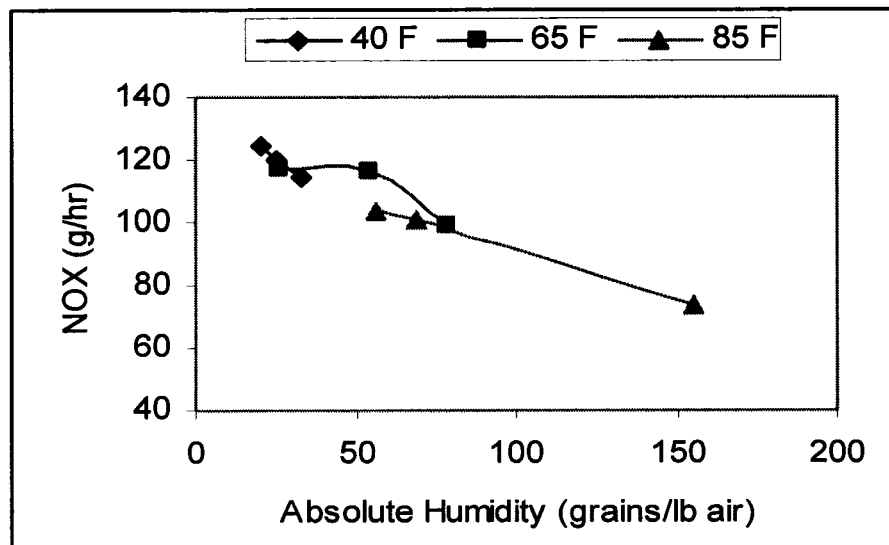


Figure 44: NO_x emissions during idling conditions for school bus with Cummins 5.9 L engine.

5.4.2.4. HC Emissions

Figure 45 shows the effect of temperature on the HC emissions for the three buses tested. As seen in this figure, temperature and humidity had no effect on HC emissions for this test. The Cummins engine produced 70 % higher HC emissions on average than the other buses. A significant amount of HC emissions are developed during the cold start of a diesel engine. A cold start is defined by the EPA as the starting of an engine, which is significantly below normal operating temperature, of significance in understanding vehicle emissions because the rate and composition of emissions vary with engine temperature. HC emissions occur mainly from poor fuel vaporization, which occurs during cold start. For the school bus idle tests, data was acquired during the final 10 minutes of the test, which never included any cold start emissions. As shown in Figure 45, since HC emissions were not averaged during cold start, there is not a significant difference in HC emissions at different ambient temperatures for this test.

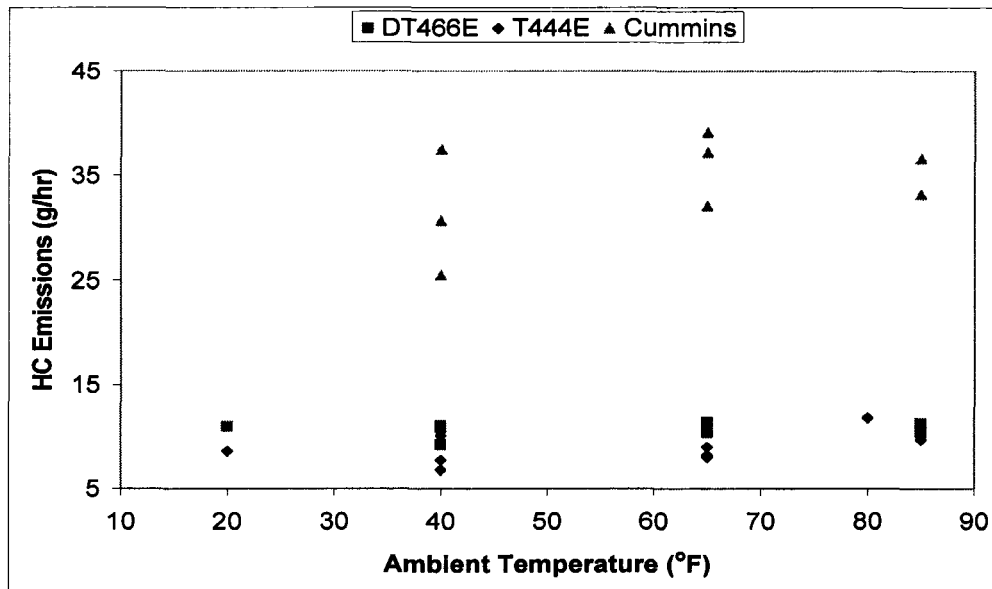


Figure 45: Effect of ambient temperature on HC emissions.

5.4.2.5. PM Emissions

The Sensors PM-300 measures particulate concentrations in number of particulates per liter for each of eight particle size ranges or “bins”. To quantify the total mass rate of emissions in g/hr, the particulate matter measured using the PM-300 must be converted to from concentration to mass. This calculation was performed assuming a spherical particle shape and an assumed average particle density. Previous studies have shown the effect of dilution factor on particle density. As particle size increases, the density of the particle decreases. Particle density can be assumed to be in between 1.1-1.2 g/cm³ over the range of particles the PM-300 can measure.⁷² The results are summarized below in Table 16.

Table 16: Average PM for the three bus engines tested

Engine	PM (g/hr)
International DT466E	1.39
International T444E	1.11
Cummins B Series	0.27

From the 33 experiments performed, there were no conclusions that could be made from ambient temperature or humidity on particulate concentrations. The Cummins B Series Bus emitted 80% less particulates than the two electronically controlled school buses. The trade off is the higher CO₂, CO, and NO_x Emissions. The Cummins school bus produced 25% higher CO₂ emissions, 60% higher NO_x emissions, and 70% higher CO and HC emissions. The NO_x: PM ratio for the Cummins engine (100:1) is similar to previous work on HDDV trucks (90:1) in the same environmental control chamber.⁷³ The International DT466E and T444E engines had much lower NO_x: PM ratios of 14:1 and 10:1, respectively.

5.4.2.6. Experimental Results – NO_x correction

Figure 42, Figure 43, and Figure 44 clearly show that there is an effect of temperature on NO_x emissions. For the engines tested in the study, as ambient temperature increases with constant relative humidity, the NO_x emissions decrease. As humidity increases, the NO_x emissions decrease.

The present school bus idle emissions study is also an integral part of larger study involving the characterization of emission reduction strategies using a mobile testing procedure. As described in detail in Chapter 6, since the experiments conducted in the mobile study are performed outside where temperature and humidity vary during the day, a correlation is necessary to correct the NO_x emissions to one set of standard conditions.

SAE standard J1243⁶⁹ focuses on the measurement of NO_x. For comparing NO_x measurements taken under conditions of varying inlet humidity, the SAE J1243 standard includes a correlation that estimates what the NO_x measurement would have been if the experiment were conducted at a standard humidity of 75 g H₂O/kg dry air and a temperature of 85°F. The correlation was first developed in a 1973 SAE paper where a number of diesel engines were studied under varying humidity and temperatures. The data were taken for an absolute humidity range of 35-125 grains H₂O/lb dry air and a temperature range of 70-115 °F. The SAE NO_x correlation is as follows:

$$NO_{corr} = \frac{NO_{wet}}{K_H} \quad 9$$

$$NO_{wet} = NO_{dry}(ppm)[1 - \alpha(F/A)] \quad 10$$

$$K_H = 1 + A(H - 75) + B(T - 85) \quad 11$$

$$A = 0.044(F/A) - 0.0038 \quad 12$$

$$B = -0.116(F/A) + 0.0053 \quad 13$$

where NO_{dry} is the measured NO_x emissions in ppm, α the hydrogen to carbon ratio (= y/x in fuel with formula C_xH_y), F/A the fuel to air ratio (dry basis), H the humidity in grains of H_2O /kg dry air and T the intake air temperature in °C.

The SAE correlation was created in order to create a NO_x correction for all diesel engines within a reasonable range of the ambient temperature and humidity constraints. The CFR40 86.1342-90, which is another correlation that only corrects for humidity variations, is as follows:

$$NO_{x\,corr} = NO_{x\,measured} * K' \quad 14$$

$$K' = \frac{1}{(1 - 0.0026 * (H - 75))} \quad 15$$

where H is the humidity in grains of H_2O in grains/lb of dry air.

The CFR40 correlation is only recommended for use in a temperature range from 68°F-85°F. Weather conditions in New Jersey fall out of both the SAE and CFR correlations. Moreover, since a wide variety of fuels, additives and exhaust gas after treatment devices will be tested in the parallel mobile emissions study at ATC, it is likely that tests will be conducted under a wider range of inlet air and humidity conditions than that recommended for either the SAE or CFR40 standard. Accordingly, a new NO_x correlation was developed from the NO_x measurements presented herein for use in the mobile emissions testing described in Chapter 6. As described below, using a similar equation to that presented in the SAE standard, three sets of “engine specific” correlation coefficients were developed corresponding to the three engines tested in this study.

In Figure 46 below, the NO_x emissions for the DT466E are shown uncorrected. The figure shows that, although all tests were conducted during identical idle conditions, NO_x concentrations vary by as much as 100 ppm with respect to experiments conducted at the

SAE standard condition of 39 % RH and 85 °F.

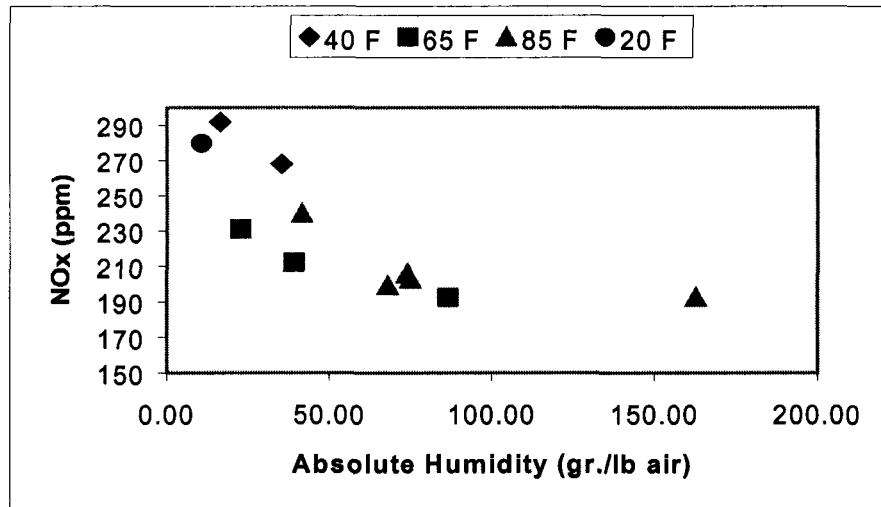


Figure 46: Uncorrected NO_x emissions (ppm) for the school bus with DT466E engine.

Since the CFR40 and SAE standards were developed for limited temperature and humidity range, extreme caution should be exercised in their use for correcting data over a wider range of conditions. This caution is of particular significance in light of the recent trend toward mobile emissions testing. The following figures show that both the SAE and CFR40 standards perform poorly outside their recommended range. In Figure 47 and Figure 48, the SAE and CFR correlations are used to correct the NO_x emissions to the standard of 85°F and 39% RH. The open symbols represent the uncorrected measurements and the closed symbols represent the corrected measurements. An effective correction factor would result in the closed symbols following a roughly horizontal line at approximately 200 ppm. As shown in Figure 47, the SAE 1243 correction factor actually increases the NO_x concentration at lower temperatures. This result underscores the danger in extending these correction factors outside the range for which they were originally developed.

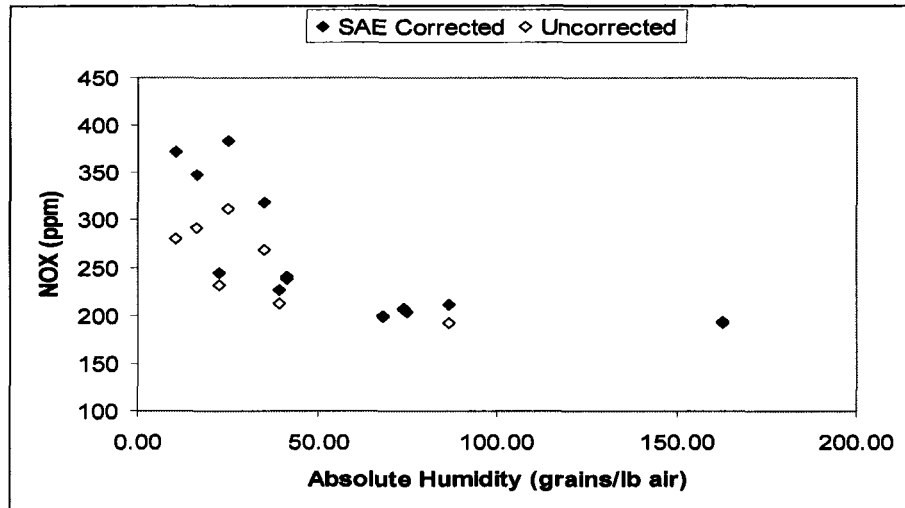


Figure 47: Corrected NO_x emissions using the SAE J1243 correction factor.

As shown in Figure 48, the CFR40 standard performs better than the SAE J1243 standard at lower temperatures, which is notable since the CFR40 correction factor does not include temperature. Figure 47 and Figure 48 show that both standards are effective for the range of temperatures for which they were developed.

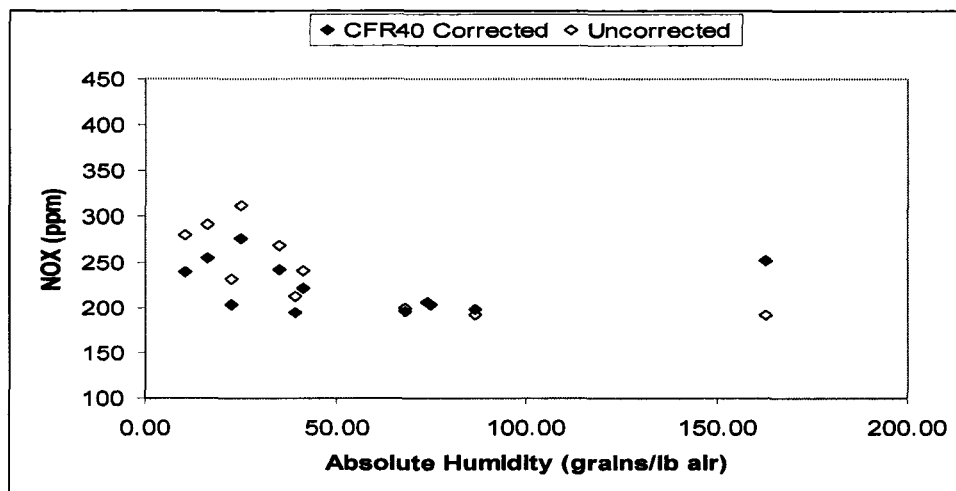


Figure 48: Corrected NO_x emission data using the CFR40 86.1342-90.

From the CFR and SAE correlations, it is apparent that in order to more accurately correct NO_x emissions over the temperature range expected during the multi-year mobile

emissions study at ATC, a new correlation would need to be developed. The new correlation follows the SAE J1243 equation format but alters the A and B values for each bus, making the correlation engine specific.

The engine specific correlations were found by measuring NO_x emission at the SAE J1243 standard conditions of 85°F and 39% RH. The constants were then calculated using a non-linear regression to correct all other experimental data to the standard condition. Figure 49 is a plot of uncorrected and corrected data for the new correction factor developed specifically for the DT466E engine. As shown in Figure 49, the new correlation factor performs well over the entire range of data, correcting NO_x concentration to within 30 ppm for a range of ambient temperatures of 20 to 85 °F and 37% to 90% RH.

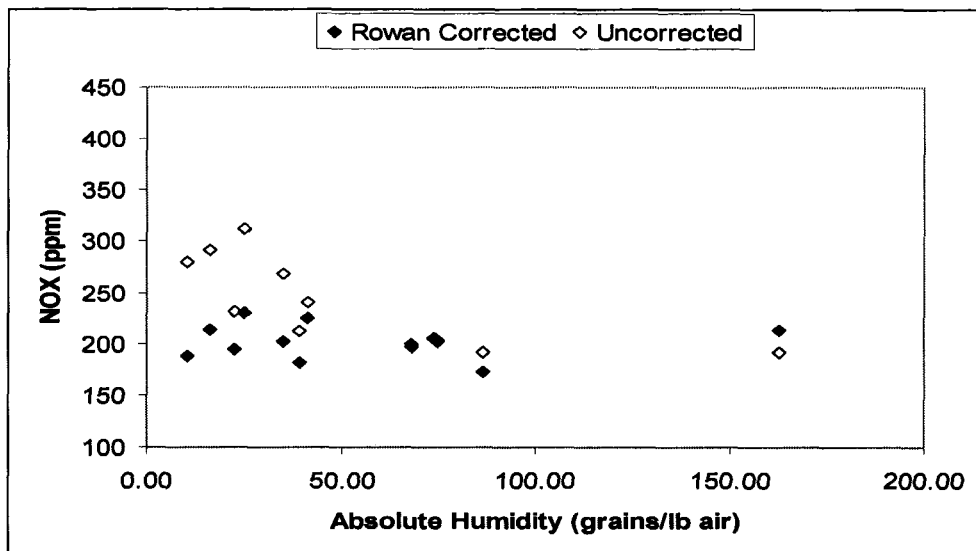


Figure 49: Engine specific corrected NO_x emissions for the DT466E.

It should be noted that the new school bus engine specific correlations are not as effective as the SAE J1243 for the temperature range (68 to 115°F) for which the SAE J1243 was developed. The same process was repeated for the remaining two buses to

develop engine specific correction factors for each. Table 17 contains the correction factor constants for each of the three buses. The new A and B values given in Table 17 can be inserted directly into the J1243 correction factor and used to correct for these specific engines.

Table 17: Engine specific values for SAE 1243 correlation

Engine	A	B
'97 International T-444E	-0.00130	-0.01323
'97 International DT466	-0.00122	-0.00664
'96 Cummins 5.9L B Series	-0.00366	0.00414

6. School Bus Mobile Emissions Testing (ATC)

6.1. Introduction

Alternative fuels such as biodiesel and ultra low sulfur diesel (ULSD) have been shown to reduce some diesel emissions in cars and trucks. The final phase of testing for this thesis was mobile testing of various alternative fuels to evaluate the emissions reduction advantages and disadvantages. The RUCSBC developed in Chapter 3 was used as the mobile emissions testing cycle for the research. NO_x emissions data collected during mobile testing was corrected for temperature and humidity using the NO_x correction factor developed in Chapter 5. Finally, mobile emission results using various alternative fuels, including B20, were compared to the test results from the Medford Township School District discussed in Chapter 4.

6.2. Experimental Procedure: Test Matrix

Experiments were conducted on the 1-Mile Loop Course at the Aberdeen Test Center in Aberdeen, Md. The course consists of a continuous asphalt surface with level, parallel 1/4-mile segments connected by 1/4-mile banked semicircular sections at each end. Data acquisition and control instrumentation were located inside the school bus. Three separate school buses were acquired and tested each with four different fuel combinations. The vehicle and engine specifications for each school bus tested are listed in Table 4. Each of the vehicles was tested with four fuels under the RUCSBC as seen in the test matrix in Table 18. Each test consisted of a single RUCSBC cycle, which has a duration of approximately 20 minutes during which HC, NO, NO₂, CO, CO₂, and PM emissions were monitored.

The Sensors Inc. SEMTECH-D mobile emissions analyzer and the Sensors Inc. PM-

300 particulate measuring device were used to acquire the above exhaust constituents during each test.

Table 18: Test matrix for each school bus

Test	Fuel Type	Fuel Makeup
1	#2 Petroleum Diesel	Low Sulfur (~360 ppm) diesel)
2	B20	20% by Volume Biodiesel, 80% by Volume #2 Low Sulfur (~360 ppm) diesel)
3	ULSD	Ultra Low Sulfur Diesel (~15 ppm)
4	B20/ULSD	20% by Volume Biodiesel, 80% by Volume Ultra Low Sulfur Diesel (~15 ppm)

6.3. Test Results

Medford Township school bus emissions tests were performed on school buses that had been operating on a certain fuel for an extended period of time. The mobile emissions testing on school buses at ATC consisted of testing alternative fuels that had just been placed into the school bus fuel system. The same three school buses were used for all four fuels tested. It should be noted that the ULSD /20% biodiesel blend was not tested for the Cummins engine due to time constraints. The procedure for switching fuels consisted of draining the fuel tank, adding the new fuel, idling the bus for ½ hour, and driving the bus for an additional ½ hour. Figure 50 is an example of raw emissions data collected during a run of the RUCSBS comparing NO_x and HC emissions over a 400 second portion of the RUCSBC.

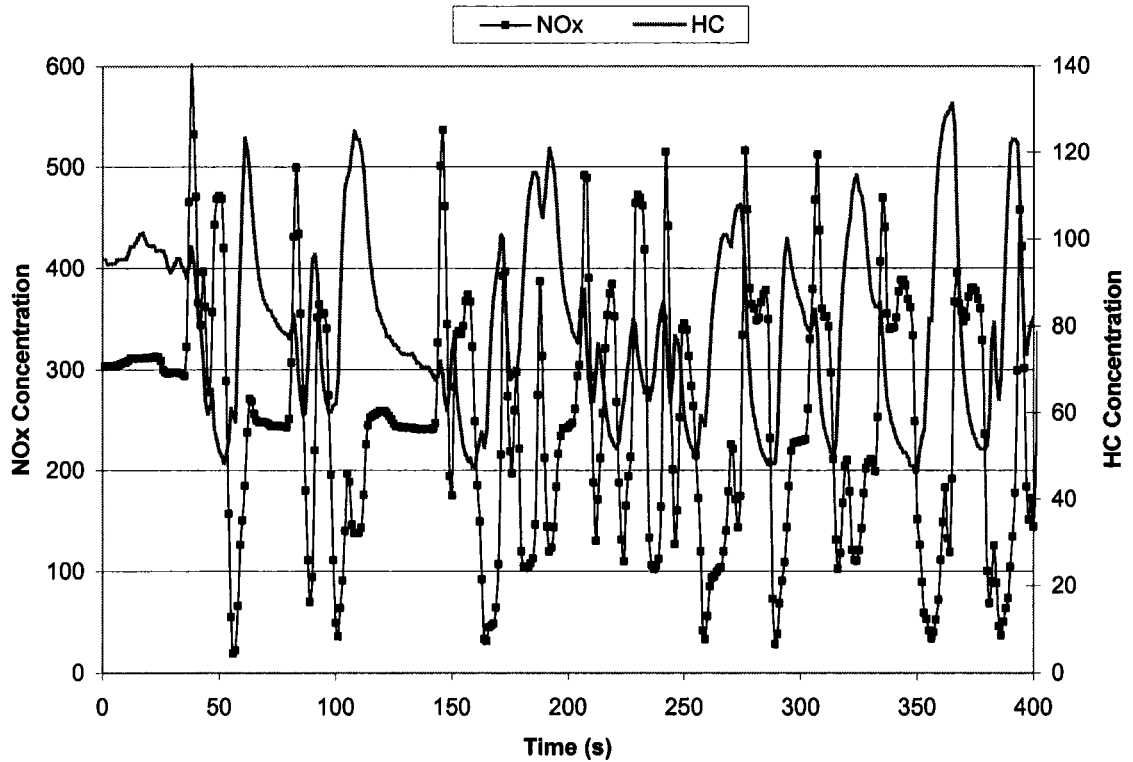


Figure 50: Raw emissions data from RUCSBC

The following fuels were tested at ATC using the RUCSBC described above: # 2 petroleum diesel, ULSD, #B20, and ULSD/ 20 % biodiesel mixture. Fuels were analyzed by the chemistry lab at ATC for density, cetane index #, viscosity, and sulfur %. Results from the fuels tests are shown in Table 19.

Table 19: Fuel properties for fuels tested at ATC.

Fuel Type	#2 Diesel	B20	ULSD
Density (g/cm ³)	.8521	.8592	.8243
Cetane Index	45.2	46.5	42.5
Sulfur %	.0431	.0409	.0049
Viscosity (mm ² /s)	2.40	2.60	1.60

6.3.1. Raw data and NO_x Correction Factors

Table 20, Table 21, and Table 22 show the raw concentration values for NO_x and HC emissions for the three buses. NO_x was corrected with three correction factors: the CFR 40, the 1973 SAE⁵⁵ standard correction factor, and a new correction factor that was developed specifically for each school bus engine used in this study⁷⁴. Note that the CFR40 only corrects for humidity while the SAE and new Rowan correction factors correct for both temperature and humidity.

As shown in Table 20, the uncorrected NO_x emissions for the T444E show little difference in respect to fuel type. The average temperature and humidity for testing was 60° F and 25 grains/lb-dry air, respectively. The Rowan correction factor corrects NO_x within 20 ppm for the four fuels tested. The CFR 40 and the SAE correction factor correct NO_x within 26 ppm and 74 ppm, respectively. The SAE correction factor actually had larger differences than the uncorrected NO_x of 33 ppm, which can be expected outside of the temperature and humidity range for which the SAE correction was designed. #2 diesel has the highest emissions of HC in ppm and the B20 has the lowest emissions of HC. Figure 51 shows the uncorrected NO_x emissions data as well as the Rowan and SAE corrected data. For a correction factor to be “successful”, corrected NO_x data should produce a horizontal line when plotted versus absolute humidity. As shown in Figure 51, the Rowan correction factor produces a near horizontal line while the SAE correction factor is almost diagonal over the tested range of absolute humidity.

Table 20: Average concentrations and various NO_x corrections for T444E

Fuel Type	Wet NO _x (ppm)	kNO _x CFR 40 (ppm)	kNO _x SAE (ppm)	kNO _x Rowan (ppm)	Wet HC (ppm)
#2	335	301	394	285	117
B20	337	294	430	267	89
ULSD	341	304	418	272	111
ULSD/ 20%Bio	368	320	468	286	95
Max. Difference	33	26	74	19	28

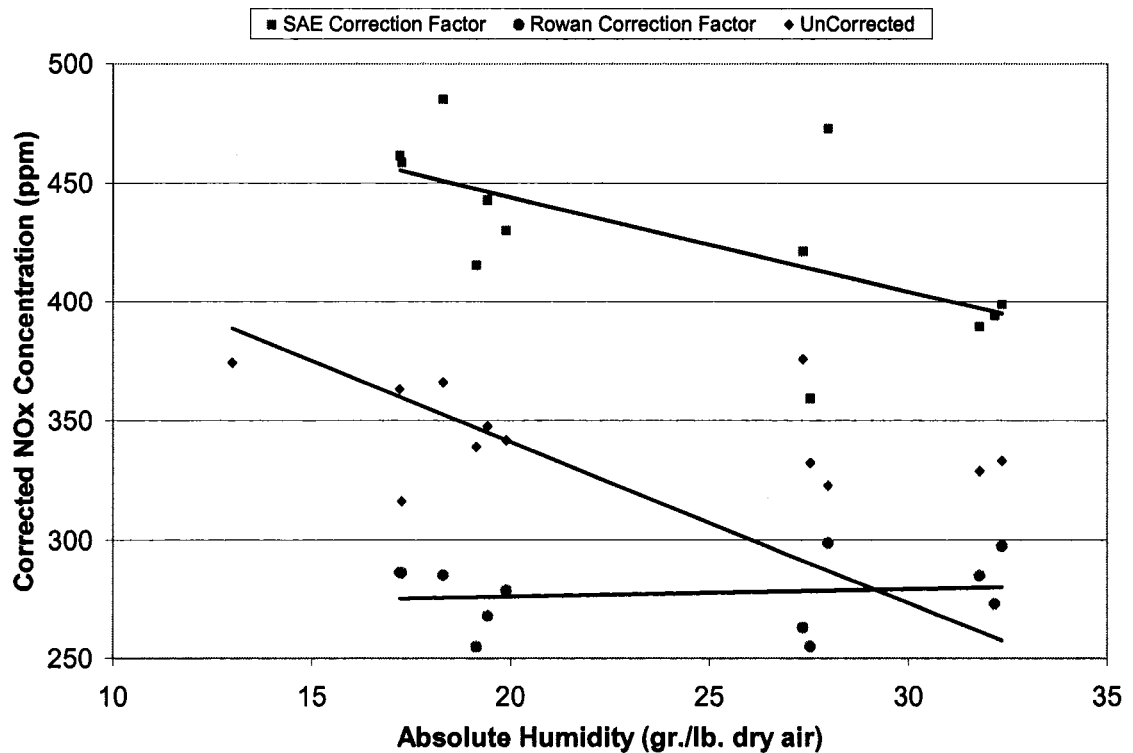


Figure 51: Raw NO_x emissions data correction factor comparison for T444E

As shown in Table 21, the uncorrected NO_x emissions show a slight difference with respect to fuel type for the DT466E bus (69 ppm). The average temperature and humidity for testing was 70° F and 65 grains/lb-dry air, respectively. The Rowan correction factor

also corrects NO_x for the DT466E bus within 20 ppm for the four fuels tested. The CFR 40 and the SAE correction factor correct NO_x within 12 ppm and 59 ppm, respectively. In this case the temperature was within the SAE correction factor limit and absolute humidity was slightly lower than the range, however the corrected NO_x was still less than the uncorrected data. #2 diesel and ULSD had the highest emissions of HC and the ULSD/ 20 % biodiesel mixture had the lowest HC emissions.

Table 21: Average concentrations and various NO_x corrections for DT466E

Fuel Type	Wet NO_x (ppm)	kNO_x CFR 40 (ppm)	kNO_x SAE (ppm)	kNO_x Rowan (ppm)	Wet HC (ppm)
#2	377	334	474	299	102
B20	371	338	435	317	96
ULSD	308	334	415	319	103
ULSD/ 20%Bio	308	326	426	303	82
Max. Difference	69	12	59	20	21

As shown in Table 22, the uncorrected NO_x emissions show a slight difference in respect to fuel type for the Cummins bus (65 ppm). The average temperature and humidity for testing was 50° F and 15 grains/lb-dry air, respectively. The Rowan correction factor corrects NO_x for the DT466E bus within 54 ppm for the three fuels tested. The CFR 40 and the SAE correction factor correct NO_x within 47 ppm and 100 ppm, respectively. The SAE correction factor actually had larger differences than the uncorrected NO_x of 69 ppm, which can be expected outside of the temperature and humidity range for which the SAE correction was designed. #2 diesel had the highest HC emissions and the B20 again had the lowest HC emissions.

Table 22: Average concentrations and various NO_x corrections for Cummins

Fuel Type	Wet NO_x (ppm)	kNO_x CFR 40 (ppm)	kNO_x SAE (ppm)	kNO_x Rowan (ppm)	Wet HC (ppm)
#2	457	398	572	525	92
B20	497	416	666	555	73
ULSD	432	369	566	501	85
Max. Difference	65	47	100	54	19

6.3.2. T444E Emissions

Figure 52 shows a representative summary of all emissions data (reported in g/mile) collected from the Semtech-D unit during alternative fuels testing of the T444E at ATC. Table 23 is a representative breakdown of all reductions and increases in emission levels using alternative fuels. The table gives the # 2 diesel emission level in g/mile and the percent increase (negative value in table) or decrease (positive value in table) for the respective alternative fuel. Figure 52 concurs with the uncorrected raw concentrations (ppm) of NO_x and kNO_x (CFR 40 correction is shown in Figure 52) that the alternative fuels tested produce only a slight variation in NO_x emissions. B20 had no affect on NO_x emissions for the T444E. ULSD and ULSD/20% biodiesel mixture slightly increased NO_x emissions 2 to 5%. CO₂ emissions were also only slightly affected by alternative fuel type (decrease of 1 to 6%).

The largest reduction in emissions from the T444E alternative fuels tests at ATC was CO and PM. The ULSD/20% biodiesel mixture produced the greatest reduction of emissions in CO by almost 70%. # 2 diesel produced 47 % higher CO emissions than B20, which is a significant increase compared to the comprehensive EPA study that found on average CO emissions were lowered by only 11 % when operating with B20.

The CO emission reduction for ULSD was 42%. PM was reduced by almost 50% for all three alternative fuels tested. For B20, the 50% reduction in PM emissions is significantly higher than the comprehensive EPA study that found average reductions of 10%.

As shown in Figure 52, HC emissions were higher for # 2 diesel in comparison with the three alternative fuels. The ULSD/20% biodiesel mixture and ULSD reduced HC by 28% and 7%, respectively, with the ULSD/20% biodiesel mixture again providing the greatest reduction. All previous research, including the Medford data given above, shows that B20 will reduce HC emissions by about 20 %.^{75,32} The 25 % reduction in HC from B20 during mobile testing using the RUCSBC concurs with those findings.

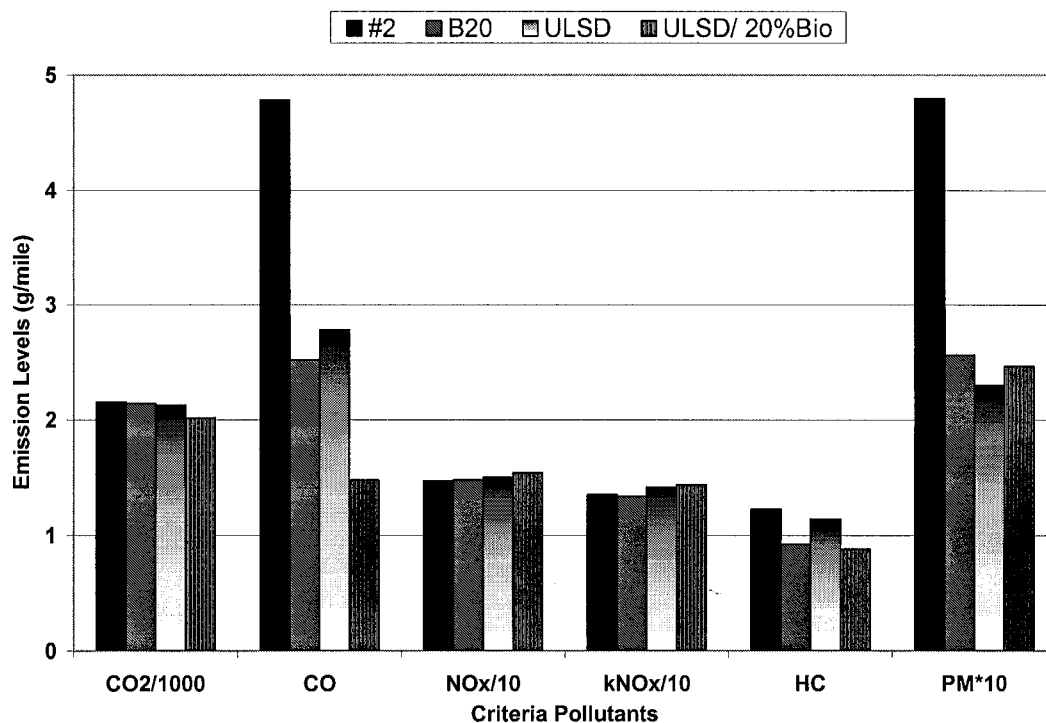


Figure 52: Average mobile emissions results for the International T444E

Table 23: Alternative fuel reductions in emission levels when compared to #2 diesel

T444E	CO₂	CO	NO_x	kNO_x	HC	PM
% Reduction						
# 2 (g/mile)	2155	4.8	14.7	13.5	1.2	0.480
B20	1	47	-1	1	25	47
ULSD	1	42	-2	-5	7	49
ULSD/20% Bio	6	69	-5	-6	28	48

6.3.3. DT466E Emissions

Figure 53 shows a representative summary of all emissions data (reported in g/mile) collected from the Semtech-D unit during alternative fuels testing of the DT466E at ATC. Table 24 is a representative breakdown of all reductions and increases in emission levels using alternative fuels. The table gives the # 2 diesel emission level in g/mile and the percent increase (negative value in table) or decrease (positive value in table) for the respective alternative fuel. Figure 53 concurs with the uncorrected raw concentrations (ppm) of NO_x and kNO_x (CFR 40 correction is shown in Figure 53) that the alternative fuels tested produce only a slight variation in NO_x emissions. B20 had no affect on NO_x emissions for the DT466E. ULSD and ULSD/20% biodiesel mixture decreased NO_x emissions 12 to 23%, almost four times more than the T444E bus. As shown in Table 24, CO and CO₂ emissions were also only slightly affected by alternative fuel type (decrease of 7% to an increase of 8%).

The largest reduction in emissions from the DT466E alternative fuels tests at ATC was HC emissions. The ULSD/20% biodiesel mixture again produced the greatest reduction of emissions in HC by 43%. # 2 diesel produced 20% higher HC emissions than B20, which is identical to the comprehensive EPA study that found on average HC

emissions were lowered by 20% when operating with B20. ULSD produced a 15% HC emission reduction.

The ULSD/20% biodiesel mixture produced the greatest reduction of PM emissions for the DT466E (by 22%), which is about half of the reduction the T444E experienced. For B20, the 3% reduction in PM emissions is slightly lower than the comprehensive EPA study that found average reductions of 10%. ULSD PM emissions increased by 22%, which may be an error since the B20 and ULSD/20% biodiesel mixtures both produced emission reductions. Since all three tests runs for the ULSD/T466E bus were performed on the same day, equipment malfunction with the PM-300 may be the cause for the unexpected results of the ULSD PM data.

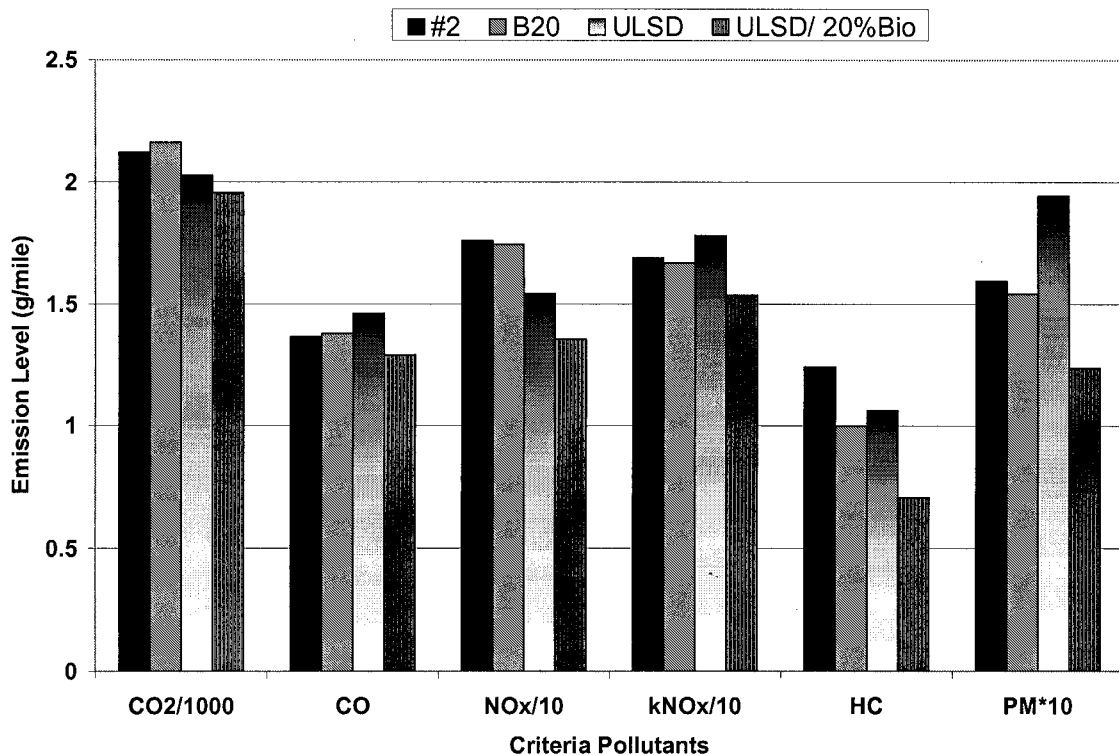


Figure 53: Average mobile emissions results for the International DT466E

Table 24: Alternative fuel reductions in emission levels when compared to #2 diesel

DT466E	CO₂	CO	NO_x	kNO_x	HC	PM
% Reduction						
# 2 (g/mile)	2120	1.4	17.6	16.9	1.2	0.159
B20	-2	-1	1	1	20	3
ULSD	4	-7	12	-5	15	-22
ULSD/20% Bio	8	5	23	9	43	22

6.3.4. Cummins 5.9L Emissions

Figure 54 shows a representative summary of all emissions data (reported in g/mile) collected from the Semtech-D unit during alternative fuels testing of the Cummins 5.9L at ATC. Table 25 is a representative breakdown of all reductions and increases in emission levels using alternative fuels. The table gives the # 2 diesel emission level in g/mile and the percent increase (negative value in table) or decrease (positive value in table) for the respective alternative fuel.

Figure 54 concurs with the uncorrected raw concentrations (ppm) of NO_x and kNO_x (CFR 40 correction is shown in Figure 54) that the alternative fuels tested produce only a slight variation in NO_x emissions. B20 increased NO_x emissions for the Cummins engine by 9%, which concurs with comprehensive EPA study that found on average NO_x emissions were increased by 2% when operating with B20. ULSD decreased NO_x emissions 14%, which is slightly lower than the reduction with the DT466E bus. As shown in Table 25, CO₂ emissions were also only slightly affected by alternative fuel type (decrease of 1% to an increase of 4%).

The largest reduction in emissions from the Cummins 5.9L alternative fuels tests at ATC was CO and HC emissions. ULSD produced the greatest reduction of emissions in CO by almost 47%, which is similar to the reduction by the T444E bus (42%). # 2 diesel

produced 28 % higher CO emissions than B20, which is a significant increase compared to the comprehensive EPA study that found on average CO emissions were lowered by only 11 % when operating with B20. # 2 diesel produced 40% higher HC emissions than B20, which is twice that of the comprehensive EPA study that found on average HC emissions were lowered by 20% when operating with B20. ULSD produced a 33% HC emission reduction.

ULSD produced an 11% reduction of PM emissions for the Cummins 5.9L engine, which is about half of the reduction the T466E experienced. For B20, the 30% reduction in PM emissions is much higher than the comprehensive EPA study that found average reductions of 10%.

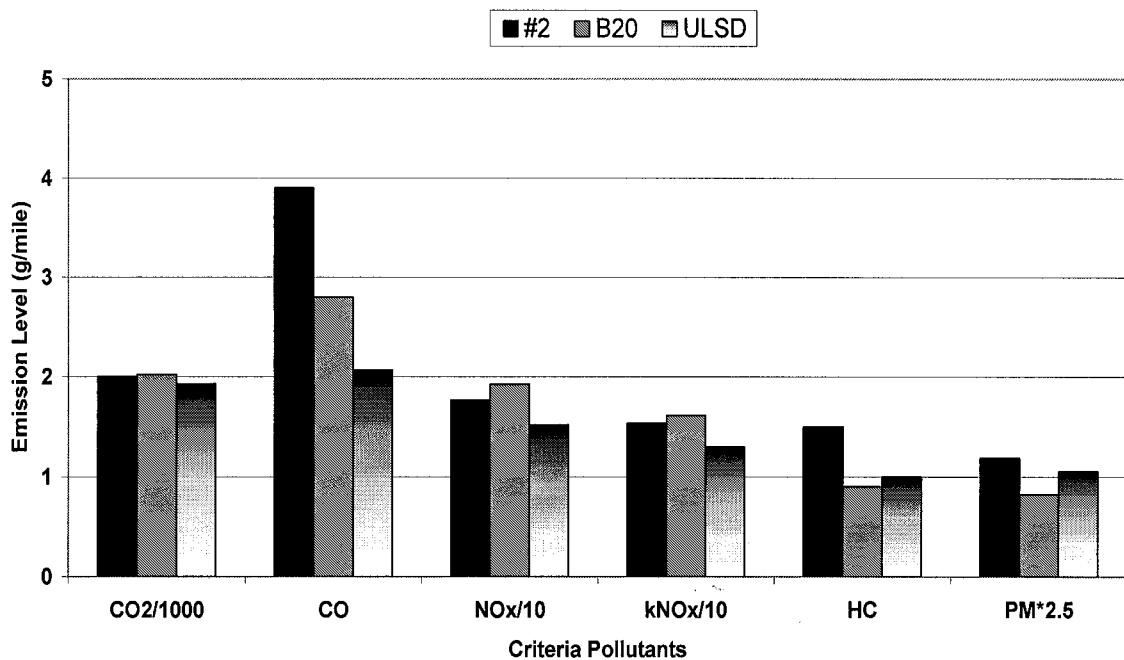


Figure 54: Average mobile emissions results for the Cummins 5.9L

Table 25: Alternative fuel reductions in emission levels when compared to #2 diesel

Cummins	CO₂	CO	NO_x	kNO_x	HC	PM
% Reduction						
# 2 (g/mile)	2005	3.9	17.6	15.4	1.5	0.476
B20	-1	28	-9	-5	40	30
ULSD	4	47	14	15	33	11

6.3.5. Mobile Emission Test Results (g/bhp-hr)

The 2007 HDDV emission standards are given in Table 26 as a comparison to the actual emission results from mobile testing. Table 26 shows how operating a school bus diesel engine using alternative fuels alone compares to the standard. CO₂ emissions are a major greenhouse gas; however the EPA does not regulate HDDV's for CO₂ emissions. CO emissions have no trouble meeting the 2007 standard with or without the use of alternative fuels.

NO_x emissions are not even close to meeting the 2007 standard, however alternative fuels such as ULSD allow for NO_x emission reduction technologies (such as NO_x catalysts) to be used. #2 diesel contains too much sulfur in the fuel to be used with most NO_x reduction technologies. HC emissions caused by #2 diesel is more than double the 2007 standard, however the three alternative fuels tested provided slight reductions to come closer to meeting the standard. PM emissions were 7 to 20 times higher than the 2007 standard for all of the fuels tested during mobile emissions testing. Since alternative fuels alone will not reduce PM anywhere near the 2007 standard, PM reduction technologies, such as particulate traps, are needed to comply. The particulate traps also require the use of low sulfur (less than 15 ppm) alternative fuels to be used correctly. Work is currently being done by a graduate student at Rowan University to

test particulate traps with alternative fuels.

Table 26: Comparison of test results with 2007 standards

444	CO ₂	CO	NO _x	HC	PM
	g/bhphr	g/bhphr	g/bhphr	g/bhphr	g/bhphr
<i>2007 Standard</i>	<i>Unregulated</i>	<i>15.5</i>	<i>0.20</i>	<i>0.14</i>	<i>0.010</i>
#2	615	1.36	4.29	0.35	0.1368
B20	618	0.73	4.42	0.27	0.0740
ULSD	594	0.78	4.46	0.32	0.064
ULSD/ 20%Bio	598	0.44	4.90	0.26	0.0730
466	CO ₂	CO	NO _x	HC	PM
	g/bhphr	g/bhphr	g/bhphr	g/bhphr	g/bhphr
<i>2007 Standard</i>	<i>Unregulated</i>	<i>15.5</i>	<i>0.20</i>	<i>0.14</i>	<i>0.010</i>
#2	632	0.41	5.70	0.37	0.159
B20	628	0.40	5.56	0.29	0.154
ULSD	606	0.44	4.90	0.32	0.195
ULSD/ 20%Bio	614	0.40	4.55	0.22	0.124

7. Conclusions and Future Work

7.1. Conclusions

7.1.1. Idle

New Jersey is continuing its efforts to meet the National Ambient Air Quality Standards (NAAQS) by investigating emission reduction strategies for school buses. One such strategy is reducing idle emissions. Little data has been collected on school buses in previous studies. In order to quantify the idling emissions, 33 tests were performed in an environmental chamber to simulate idling conditions experience throughout the course of a school year.

There are currently approximately 11,000 school buses in use in the state of NJ. Based on the idle emissions measurements presented herein (assuming an average idle time of one hr/day), the current NJ school bus fleet produces approximately 9.3 million kg of CO₂, 90,000 kg CO, 150,000 kg NO_x, 35,000 kg HC and 2,145 kg PM per calendar school year of 180 days.

In terms of the financial burden, a one-hour reduction of idling time per school bus per day for each of the 11,000 buses in NJ would result in an annual statewide cost savings of approximately \$1.5 million. This calculation is based on an average school bus fuel consumption of 0.5 gallons of diesel fuel per hour and a price of \$1.50 for #2 diesel⁷⁶.

In addition, the following conclusions were also found for the school buses tested in this study:

- As fuel consumption increases, CO₂ and CO emissions increase.
- As ambient temperature increases, CO emissions decrease due to a more complete

conversion of CO to CO₂.

- As expected, results showed that for each of the buses tested, as humidity increased, NO_x emissions decreased. For the most part as temperature increased, NO_x emissions also decreased.
- Hydrocarbon (HC) and Particulate matter (PM) measurements did not show any relationship between temperature, humidity, or fuel consumption.
- The SAE J1243 and CFR 40 86.1342-90 correction factors for NO_x emission perform poorly when applied to temperature and humidity ranges outside those for which they were developed, particularly when applied to experiments conducted at low temperatures.
- A modification of the SAE J1243 correlation resulting in engine specific correlation constants was created for the DT444E, DT466E, and Cummins 5.9L school bus engines was successfully used for mobile school bus testing.

7.1.2. Mobile

With increasing pressure to meet the National Ambient Air Quality Standards (NAAQS) set by USEPA, New Jersey continues to actively research and develop strategies to help meet the standards, which may include alternative fuels and after treatment devices. However, prior to the present study, very little data was available to quantify emission levels for school buses under realistic mobile testing conditions. Moreover, prior to the present study, there were no mobile testing cycles developed for school buses to be tested. This study now provides a composite test cycle for school buses as well as emissions data for three alternative fuels and #2 petroleum diesel acquired using a repeatable, mobile school bus cycle. The composite test cycle can also

be used for testing with a chassis dynamometer.

To obtain additional alternative fuel mobile emissions data, three B20 fueled buses and one # 2 petroleum diesel fueled bus were tested on-road within the Medford, NJ school district. In parallel to these tests, three buses were tested at the Aberdeen Test Center using three alternative fuels and a baseline # 2 petroleum diesel. The following major conclusions were found:

- CO₂ emissions were not affected by the alternative fuels tested; however Biodiesel provides CO₂ benefits because it is a renewable fuel.
- NO_x emissions were slightly affected by the alternative fuels tested, however ULSD and ULSD/20% Biodiesel allow for use of NO_x reduction technologies.
- HC emissions were significantly reduced for all buses by all alternative fuels by 7 to 43%.
- B20 and ULSD reduced CO and PM emissions by an average of 30 - 40% for the T444E and Cummins.
- ULSD/20% Biodiesel provided significant reductions in CO and PM emissions by 70% and 50%, respectively, for the T444E.
- ULSD/20% Bio reduced PM emissions by 22% for the DT466E.
- No affect of alternative fuels on CO emissions for the DT466E.
- B20 had no affect on PM emissions for the DT466E.
- ULSD raised PM emissions by 22% for the DT466E.

7.1.3. Thesis

Mobile emissions testing with alternative fuels and the study of idle emissions provided significant research results for the school bus emissions field. ULSD and

ULSD/20% biodiesel was tested and compared to #2 diesel in three different school buses for the first time. Results found that the ULSD/20% biodiesel mixture alone has the ability to provide emission reductions and potential to combine with other emission reduction technologies for further reductions. The first school bus mobile emissions cycle to represent rural, urban, and suburban region of NJ was also created. These are the major thesis conclusions:

- Regulation of school bus idling could provide significant emission reduction.
- The Rowan University NO_x correction factor successfully corrects NO_x emissions over a wide range of temperatures and humidity's.
- The RUCSBC provides an accurate and repeatable composite school bus testing cycle for a variety of regions, that can be used for future mobile testing or chassis dynamometer testing.
- Alternative fuels have the potential to reduce emissions from diesel engines.
- Unfortunately, alternative fuels alone do not provide significant emission reductions to meet 2007 standards.
- Future work includes incorporating the alternative fuels and the RUCSBC with various after treatment devices and technologies such as NO_x catalysts and particulate traps.

7.2. Future Work

The research presented herein is the first phase of the Rowan/NJDOT diesel emission reduction study. The next phase will be to mobile test existing diesel after treatment devices, such as the Johnson Matthey CRT and Engelhard DPX particulate trap, among other reduction strategies. The results of this testing will be compared to the results

presented in this paper in order to propose the most effective emission reduction method for school buses. If further testing is required, a chassis dynamometer may be purchased to further quantify emission-testing results. At the end of testing emission reduction devices it is possible that higher blends ($> B20$) of biodiesel will be tested with specifically designed gaskets for the engines.

When the most effective emission reduction strategies and combinations for NJ school buses are found, they will be proposed to the NJDOT and NJ school districts. An interactive website will then be developed for school districts to find the best reduction strategies for their region and their particular school bus engine. The same mathematical model that will be used on the website for emission calculations will also be sent out to the schools as an interactive CD-ROM.

8. References

-
- ¹ Heavy-Duty Engine Emissions in the Northeast”, NESCAUM, May 1997.
- ² “School Bus Safety: Crash Worthiness Research”, National Highway Traffic Safety Administration (NHTSA), April 2002.
- ³ “Clean School Bus USA”, USEPA, <http://www.epa.gov/otaq/schoolbus/basicinfo.htm>, viewed August 25 2003.
- ⁴ Clements, J.S., “School bus carbon monoxide intrusion”, Off. State Vehicle. Program, National Highway Traffic Safety Administration., Washington, DC, USA. Avail. NTIS. Report (1978), (DOT-HS-803705; Order No. PB-291156), 60 pp.
- ⁵ Northeast Florida Regional Planning Council, viewed October 10, 2003. http://www.nefrpc.org/AFVweb/case_study_6.htm.
- ⁶ Brown, K. F., Rideout, G.R., Turner, J.E., “Urban driving cycle results of retrofitted diesel oxidation catalysts on heavy duty vehicles: one year later.” SAE, [Spec. Publ.] SP (1997), SP-1227 (Diesel Exhaust Aftertreatment 1997), 69-82.
- ⁷ Clark, N.N., Gautam, M., Wang, W., Boyce, J.A., Lyons, D.W., “Emissions performance of natural gas and diesel fueled school buses with Cummins 8.3 liter engines,” ICE (Am. Soc. Mech. Eng.) (1999), 32-2 (Experimental Studies in Engines and Natural Gas and Alternative Fuels, Vol. 2), 17-24.
- ⁸ Frey, H. Christopher, “Quantification of uncertainty in remote sensing-based school bus CO and hydrocarbon emission factors.” Proc., Annu. Meet. - Air Waste Manage. Assoc. (1997), 90th RP14307/1-RP14307/16.
- ⁹ LeTavec, C., Uihlein, J., Vertin, K., Chatterjee, S., “Year-long evaluation of trucks and buses equipped with passive diesel particulate filters”, Paper # 2002-01-0433, SAE 2002 World Congress.

-
- ¹⁰ Diesel Technology Forum, Clean Diesel Solutions for Today's Engines", viewed August 25, 2003. <http://www.dieselforum.org/retrofit/Schoolbus.html>.
- ¹¹ EPA Region 2 State of the Environment 1998, viewed September 15, 2003. <http://www.epa.gov/region02/soer/>
- ¹² EPA Region 2 Air, State Implementation Plan, viewed September 15, 2003. <http://www.epa.gov/region02/air/sip/>
- ¹³ EPA OTAQ, Mobile Source Emissions - Past, Present, Future, viewed September 15, 2003. <http://www.epa.gov/otaq/invtory/overview/examples.htm>.
- ¹⁴ EPA Voluntary Diesel Retrofit Program, Overview, viewed September 15, 2003. <http://www.epa.gov/otaq/retrofit/glossary.htm>.
- ¹⁵ Jarret, R.P., Clark, N.N. "Evaluation of Methods for Determining Continuous Particulate Matter from Transient Testing of Heavy-Duty Diesel Engines." SAE Technical Paper, 2001-01-3575, (2001)
- ¹⁶ Groves, J., Cain, J.R., "A Survey of Exposure to Diesel Engine Exhaust Emissions in the Workplace." Elsevier Science Ltd on behalf of British Occupational Hygiene Society, (2000)
- ¹⁷ IARC (International Agency for Research on Cancer) Diesel and Gasoline Engine Exhausts and some Nitroarenes. IARC, Lyon, France, ISBN 92 832 1246 0, 1998.
- ¹⁸ Bradley, B., "A Comparison of Steady State and Transient Emissions from a Heavy-Duty Diesel Engine", A Thesis Presented to The College of Engineering and Mineral Resources at West Virginia University, 2002.
- ¹⁹ Code of Federal Regulations, 40, Part 86, Subpart N, "Protection of Environment," U.S. Government Printing Office, 1998.

²⁰ "Engine Mechanics, Engine Flywheel", viewed April 2004.

http://www.tpub.com/content/engine/14037/css/14037_107.htm

²¹ Diesel and Industrial Dynamite Dynamometers, viewed February, 2002.

<http://www.land-and-sea.com/diesel-dynamometer/diesel-dynamometer.htm>

²² Personal contact, Hank Fulmer, Power Test Inc, January 2003.

²³ Personal visit, Johnson and Towers Inc., Mt Laurel, NJ, January 2003.

²⁴ Personal contact, Michael Caldwell, Mustang Dynamometers, January 2003.

²⁵ Personal contact, Schenck Pegasus, January 2003.

²⁶ Fleet Owner, "EPA's take on 2007", viewed September 15, 2003.

http://fleetowner.com/ar/fleet_epas/.

²⁷ EPA Civil Enforcement, "Fact Sheet Diesel Engine Settlement:", viewed September 20, 2003. <http://www.epa.gov/compliance/civil/programs/caa/diesel/factsheet.html>.

²⁸ EPA National News," EPA Announce 1 Billion Dollar Settlement With Diesel Engine Industry, viewed September 15, 2003.

<http://yosemite.epa.gov/opa/admpress.nsf/b1ab9f485b098972852562e7004dc686/93e9e651adeed6b7852566a60069ad2e?OpenDocument>

²⁹ Dieselnet, Diesel Engine Glossary, viewed September 15, 2003.

<http://www.dieselnet.com/gl-a.html>.

³⁰ McCormick, R., "Renewable Diesel Fuels: Status of Technology and R&D Needs", US DOE, 8th Diesel Emissions Reduction Conference (DEER), San Diego, CA, August 2002.

³¹ Official Site of the National Biodiesel Board, Biodiesel FAQ, viewed September 15, 2003. <http://www.biodiesel.org/resources/faqs/>.

³² Graboski, M.S., McCormick, R.L., "Combustion of Fat and Vegetable Oil Derived Fuels in Diesel Engines", Prog. Energy Combustion Science Vol. 24 pp 125-164, 1998.

³³ The Puget Sound Clean Cities Coalition, "Comparison to Biodiesel and Ultra Low Sulfur Diesel", viewed August 25 2003.
<http://www.pugetsoundcleancities.org/Biodiesel2.htm>.

³⁴ Bunkerworld, Cloud Point Definition,
http://www.bunkerworld.com/technical/tech_pp_3.htm.

³⁵ Assessment and Standards Division Office of Transportation and Air Quality U.S. Environmental Protection Agency, "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions", EPA420-P-02-001, Oct. 2002.

³⁶ Personal Contact, Joe Biluck, Medford New Jersey School District Director of Operations, January 2003.

³⁷ "EPA Verified Retrofit Technologies", viewed October 2003.
<http://www.epa.gov/otaq/retrofit/retroverifiedlist.htm>

³⁸ Chatterjee, S. "Emission reductions and operational experiences with heavy-duty diesel fleet vehicles retrofitted with continuously regenerated diesel particulate filters in Southern California", Paper # SAE 2001-01-0512, SAE World Congress 2001.

³⁹ "Catalyst-Based Diesel Particulate Filters and NOx Adsorbers: A Summary of the Technologies and the Effects of Fuel Sulfur." Manufacturers of Emissions Controls ASSN. Aug 14, 2000. <http://www.meca.org>

⁴⁰ Warren, J. P., Allansson, R., Hawer, P.N., Wilkins, J.J. "Effects on after-treatment on particulate matter when using the Continuously Regenerating Trap (CRT™)" S491-006-1998.

⁴¹ Brace, Matthew. "Into the Trap. A new affordable exhaust filter system could hold the key to significantly cleaner diesel emissions." Green Futures. Johnson Matthey.

⁴² DieselNet Technology Guide, "CRT Filter", viewed September 25, 2003.
http://www.dieselnet.com/tech/dpf_cat.html.

⁴³ "The Impact of Gasoline Fuel Sulfur on Catalytic Emission Control Systems."
Manufacturers of Emission Controls Association. Washington, DC. Sept 1998.

⁴⁴ Vertin, K., Chandler, K., LeTavec, C., Goguen, S., Keshki-Hynnila, D., Chatterjee, S.,
Smith, G., Hallstrom, K. "Class 8 Trucks Operating On Ultra-Low Sulfur Diesel
With Particulate Filter Systems: A Fleet Start-Up Experience" 2000-02-2821

⁴⁵ "Innovative Emissions Control Solutions for On-Highway Applications." Engelhard
Corporation, viewed October 31, 2002. <http://www.engelhard.com>.

⁴⁶ Engelhard Corporation, "Engelhard Emission Control Products", viewed September
25, 2003. <http://www.dieselnet.com/engelhard/products.html>.

⁴⁷ "Survey of School Buses in NJ", Polk Automotive Intelligence of Detroit, March 2002.

⁴⁸ Clark, Nigel N., et. al., "Transient Emissions Comparisons of Alternative Compression
Ignition Fuels." SAE Technical Paper 1999-01-1117 (1999).

⁴⁹ Lat, R.J., "Emissions and performance characteristics of a 4-stroke, direct injected
diesel engine fueled with blends of biodiesel and low sulfur diesel fuel", Paper # SAE
950054, SAE International Congress and Expo, 1995.

⁵⁰ Schumacher, L., "100,000 miles of fueling 5.9L Cummins engines with 100%
biodiesel", Paper # SAE 962233, SAE International Truck and Bus Meeting and
Exposition 1996.

⁵¹ How Stuff Works, "How Turbos Work", viewed September 25, 2003.
<http://auto.howstuffworks.com/turbo4.htm>

⁵² Cummins Medium and Heavy Trucks, viewed September 25, 2003.
<http://www.cummins.com/na/pages/en/products/trucks/isb.cfm>.

⁵³ Aberdeen Test Center Facilities/Capabilities Guide, viewed August 21, 2002.
http://www.atc.army.mil/fac_guide/facilities/envcham4.html.

⁵⁴ "Semtech-D Operator's Manual." Revision 5.1, Sensors, *Inc.*

⁵⁵ Krause, S.R., Merrion, D.F., Green, G.L., "Effect of Inlet Air Humidity and Temperature on Diesel Exhaust Emissions", International Automotive Engineering Congress January 8, 1973. SAE Paper # 730213

⁵⁶ "PM-300 Operator's Manual." Revision 5.1, Sensors, Inc.

⁵⁷ Aberdeen Test Center Facilities/Capabilities Guide, viewed August 21, 2002.
http://www.atc.army.mil/fac_guide/facilities/facilities.html.

⁵⁸ Emissions Standards Applicability and Test Cycles, viewed August 25, 2003
<http://www.dieselnets.com/standards/us/hd.html>.

⁵⁹ Nine, R.D., N.N. Clark, J.J. Daley, C.M. Atkinson. "Development of a Heavy-Duty Chassis Dynamometer Driving Route." Proc Instn Mech Engrs Vol. 213 Part D 1999.

⁶⁰ Brown, Steve, Chris Bryett, Mike Mowle. "Proposed Diesel Vehicle Emissions National Environmental Protection Measure Preparatory Work: In-Service Emissions Performance; Drive Cycle." National Environmental Protection Council Service Corporation. EPA NSW, ISBN 0 642 32323 2. March 1999.

⁶¹ Davies, S., Sparks, S., Donnelly, J., "Identification of Typical Drive Cycles for Diesel Vehicles: Final Report", CSIRO Mathematical and Informational Science Macquarie University Campus, Feb 1999.

⁶² "Urban and Rural Population & Housing Units New Jersey, Counties, and Municipalities 2000." New Jersey State Data Center, April 2003.

⁶³ New Jersey Schools Elementary, middle and high school information, viewed August 15, 2003. <http://www.greatschools.net/modperl/go/NJ>.

⁶⁴ Akasaka, Y., Suzuki, T., Sakurai, Y., "Exhaust Emissions of a DI Diesel Engine Fueled with Blends of Biodiesel and Low Sulfur Diesel Fuel", International Fall Fuels & Lubricants Meeting & Exposition, Oct. 1997. SAE Paper # 972998.

⁶⁵ "Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus," NREL/SR-580-24089 UC Category 1503, USDA & USDOE May 1998.

⁶⁶ Pekula, N, B. Kuritz, J. Hearne, A. J. Marchese, R. P. Hesketh, "The Effect of Ambient Temperature, Humidity, and Engine Speed on Idling Emissions from Heavy-Duty Diesel Trucks," SAE 2003-01-0290.

⁶⁷ Cook, B., "Airborne Toxic Control Measure to Limit School Bus Idling and Idling at Schools", California Air Resources Board, December 2002.

⁶⁸ Aberdeen Test Center Facilities/capabilities Guide, http://www.atc.army.mil/fac_guide/facilities/envcham4.html, viewed August 21, 2002.

⁶⁹ "Measurement of Carbon Monoxide, Carbon Dioxide, and Oxides of Nitrogen in Diesel Exhaust." SAE J1243, (1995)

⁷⁰ IARC (International Agency for Research on Cancer) Diesel and Gasoline Engine Exhausts and some Nitroarenes. IARC, Lyon, France, ISBN 92 832 1246 0, 1998.

⁷¹ Groves, J. and J.R. Cain, "A Survey of Exposure to Diesel Engine Exhaust Emissions in the Workplace," Ann. Occup. Hyg., 44(6) pp. 435-447 (2000).

⁷² Virtanen, Annele "Effective density of diesel exhaust particles as a function of size" SAE 2002-01-0056, (2002).

⁷³ Storey, J. Thomas, J., Lewis Sr., S. "Particulate Matter and Aldehyde Emissions from Idling Heavy Duty Diesel Trucks", SAE Paper #2003-01-0289, SAE World Congress, March 2003.

⁷⁴ Toback, A.T., Hearne, J.S., Hesketh, R.P., Marchese, A.J., The Effect of Ambient Temperature and Humidity on Idling Emissions from Diesel School Buses", SAE World

Congress, March 2004.

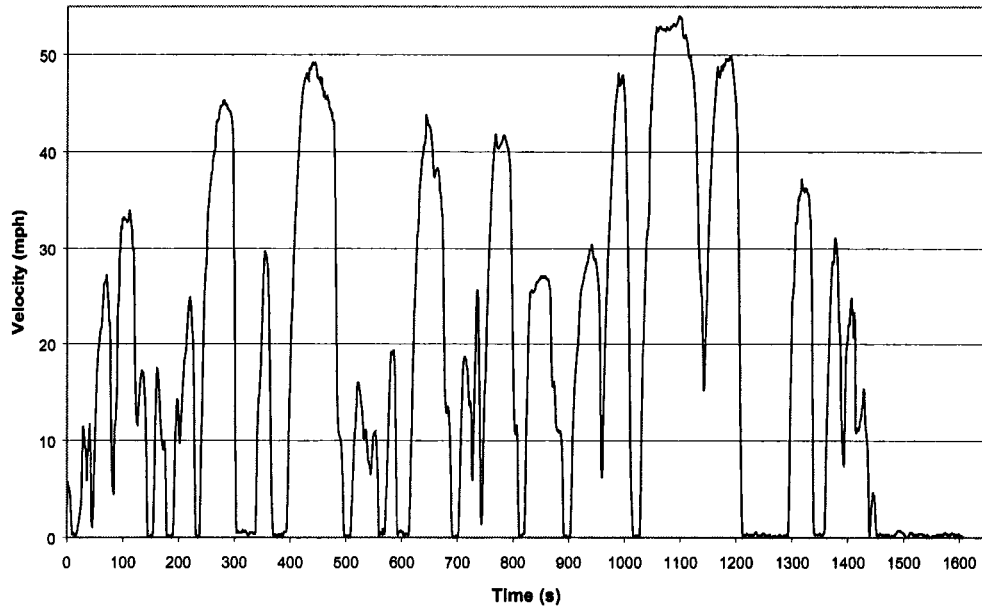
⁷⁵ Assessment and Standards Division Office of Transportation and Air Quality U.S. Environmental Protection Agency, “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions”, EPA420-P-02-001, Oct. 2002.

⁷⁶ US Department of Energy, “Gasoline and Diesel Fuel Update”, viewed August 16, 2003. <http://tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp>.

Appendix A: GPS and Map Source Data

Prototypical School District 1: Medford Township Raw Data

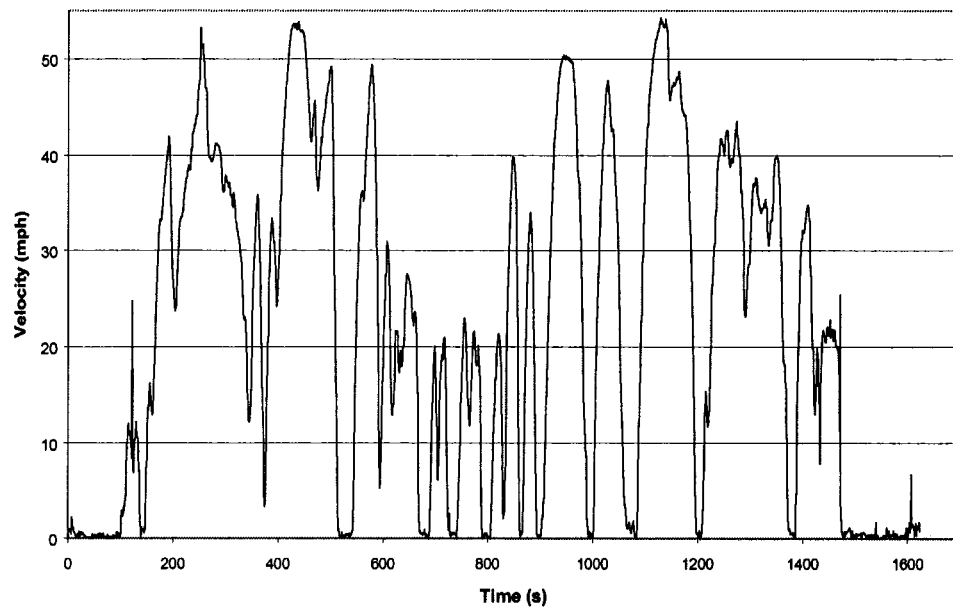
Velocity vs. Time (1 Route)



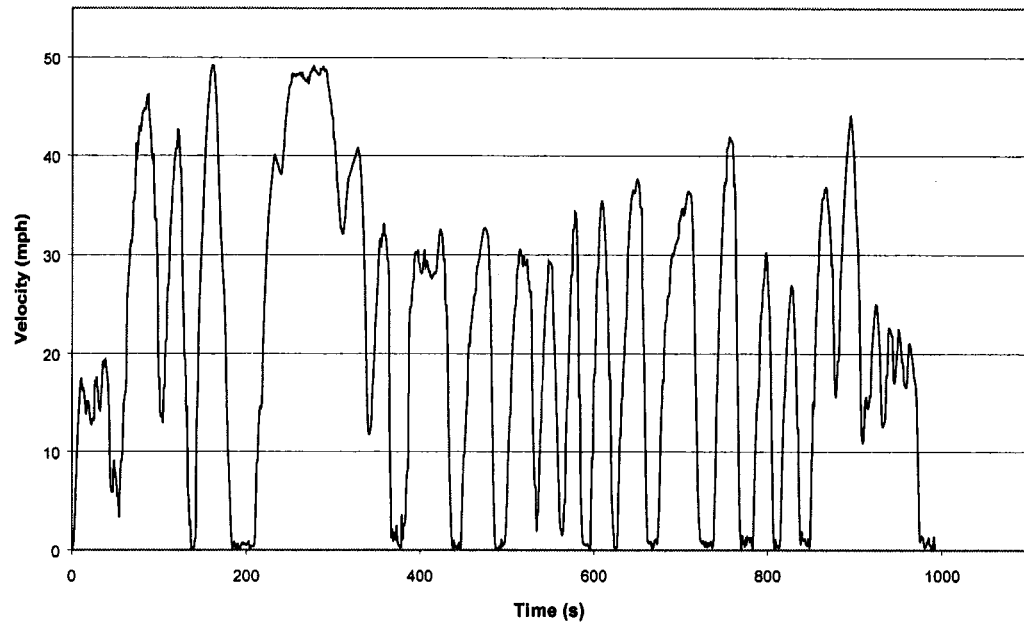
Medford Township School District Route

Prototypical School District 2: Washington Township Raw Data

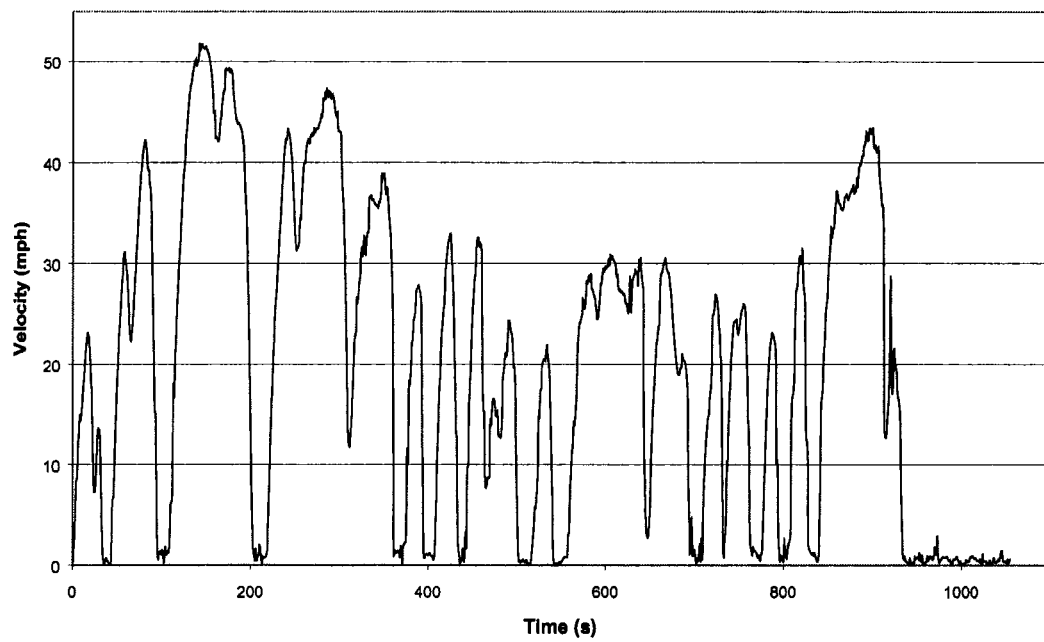
Velocity vs. Time (4 Unique Routes)



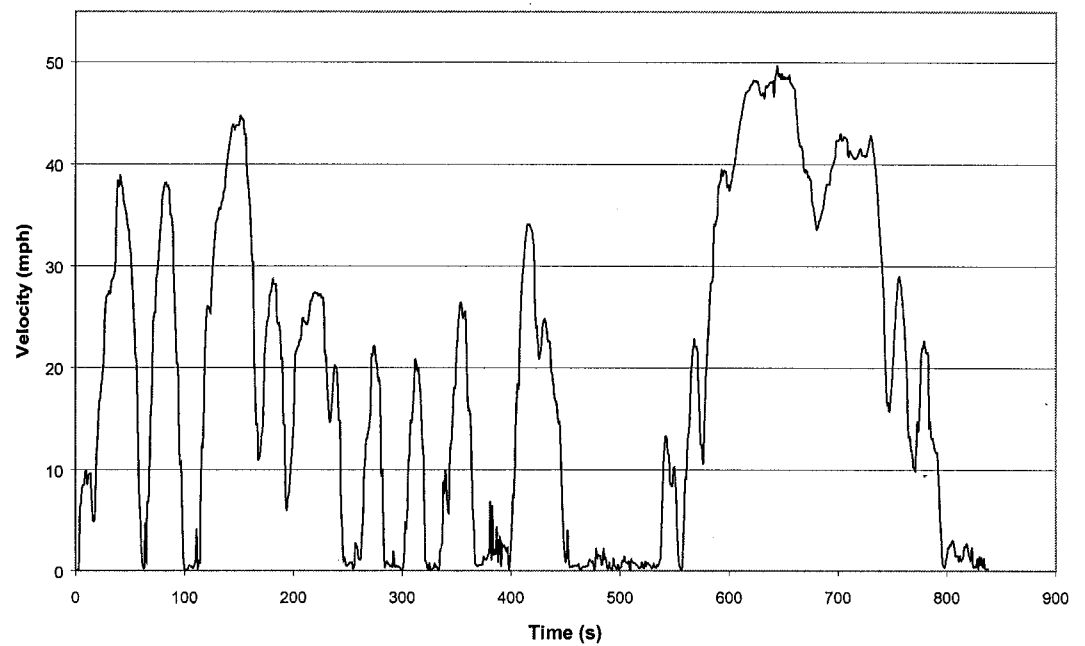
Washington Township School District (Bus Depot to High School Route)



Washington Township School Route (High School to Middle School)

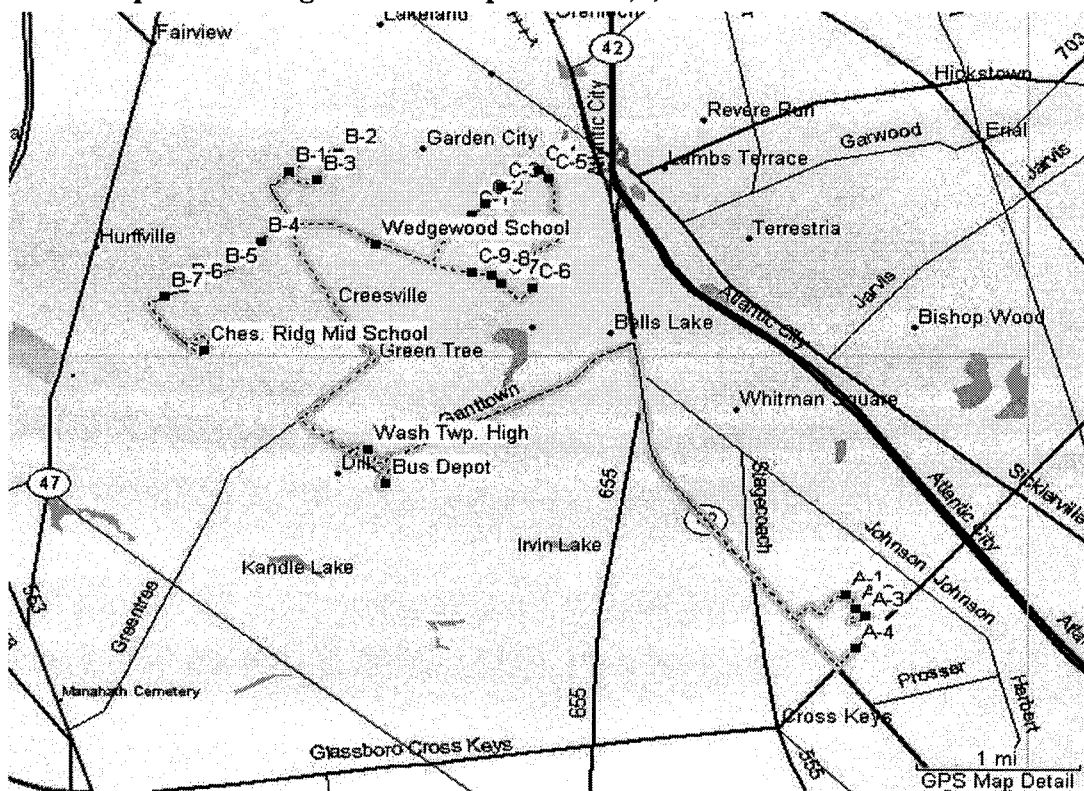


Washington Township School Route (Middle School to Elem. School)



Washington Township School Route (Elem. School to Bus Depot)

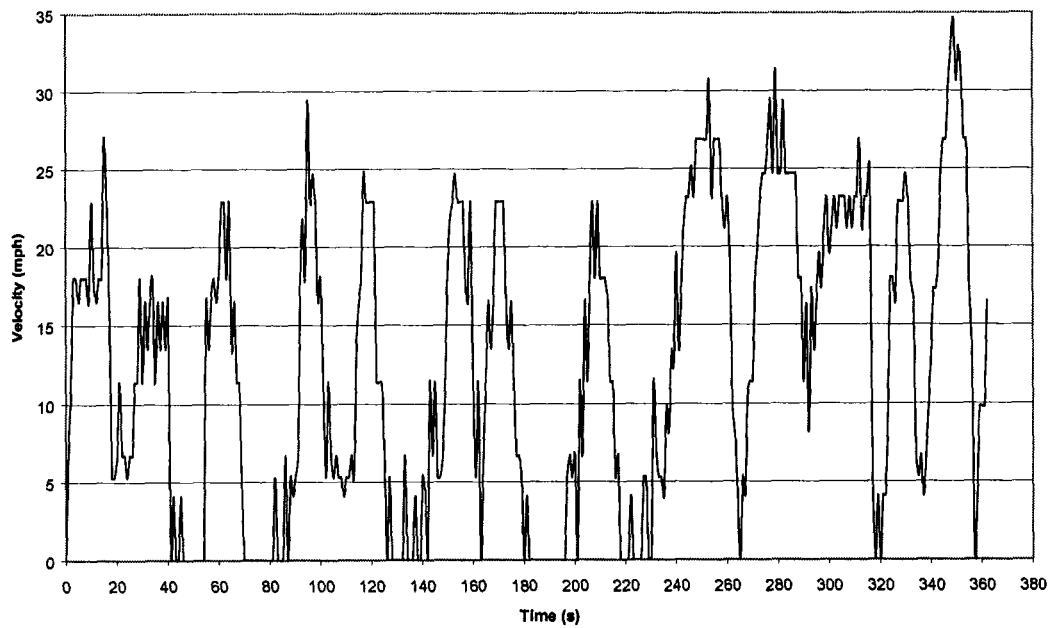
GPS Map of Washington Township Routes 1,2, and 3 Combined



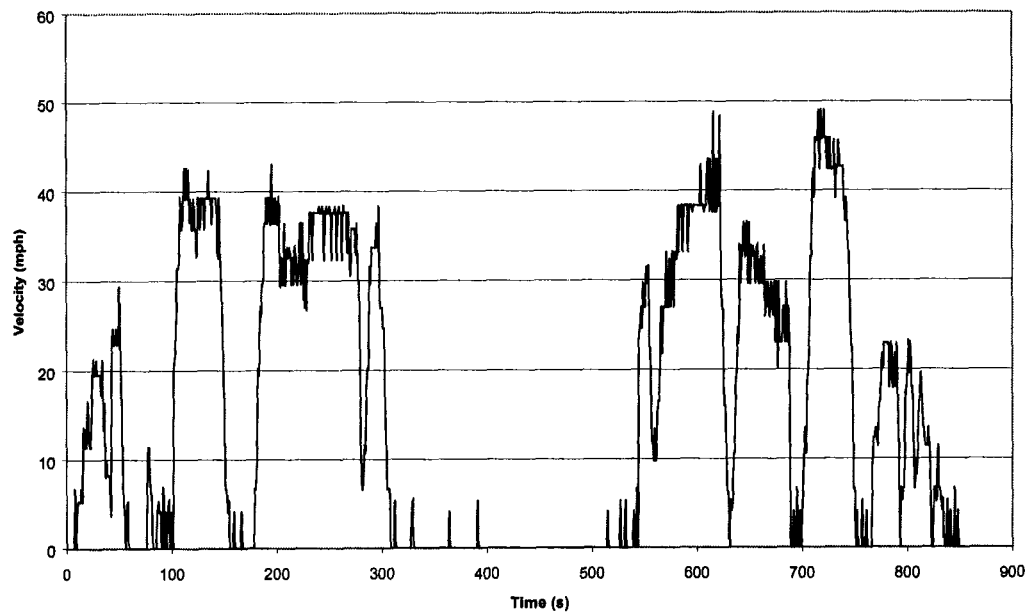
Washington Township Runs 1,2, and 3 GPS Map

Prototypical School District 3: Glassboro Raw Data

Velocity vs. Time (2 Unique Routes)



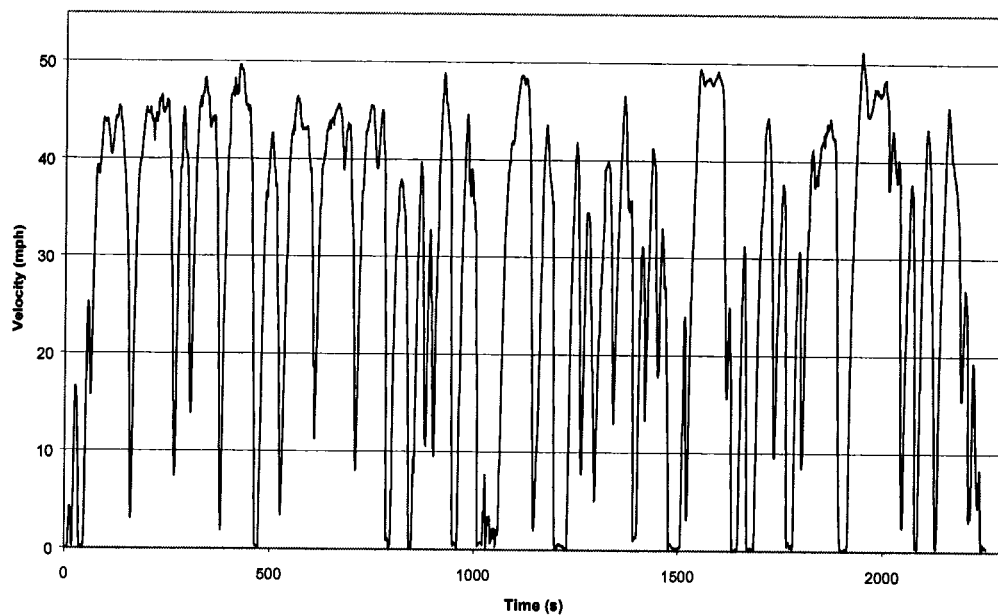
Glassboro School District Route 1



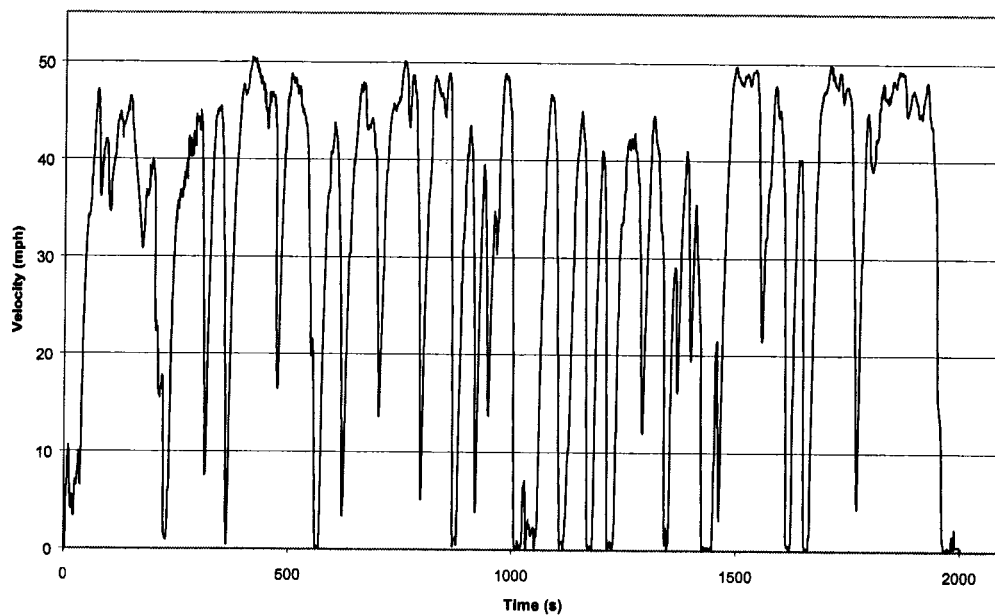
Glassboro School District Route 2

Prototypical School District 4: Pittsgrove Raw Data

Velocity vs. Time (2 Unique Routes)

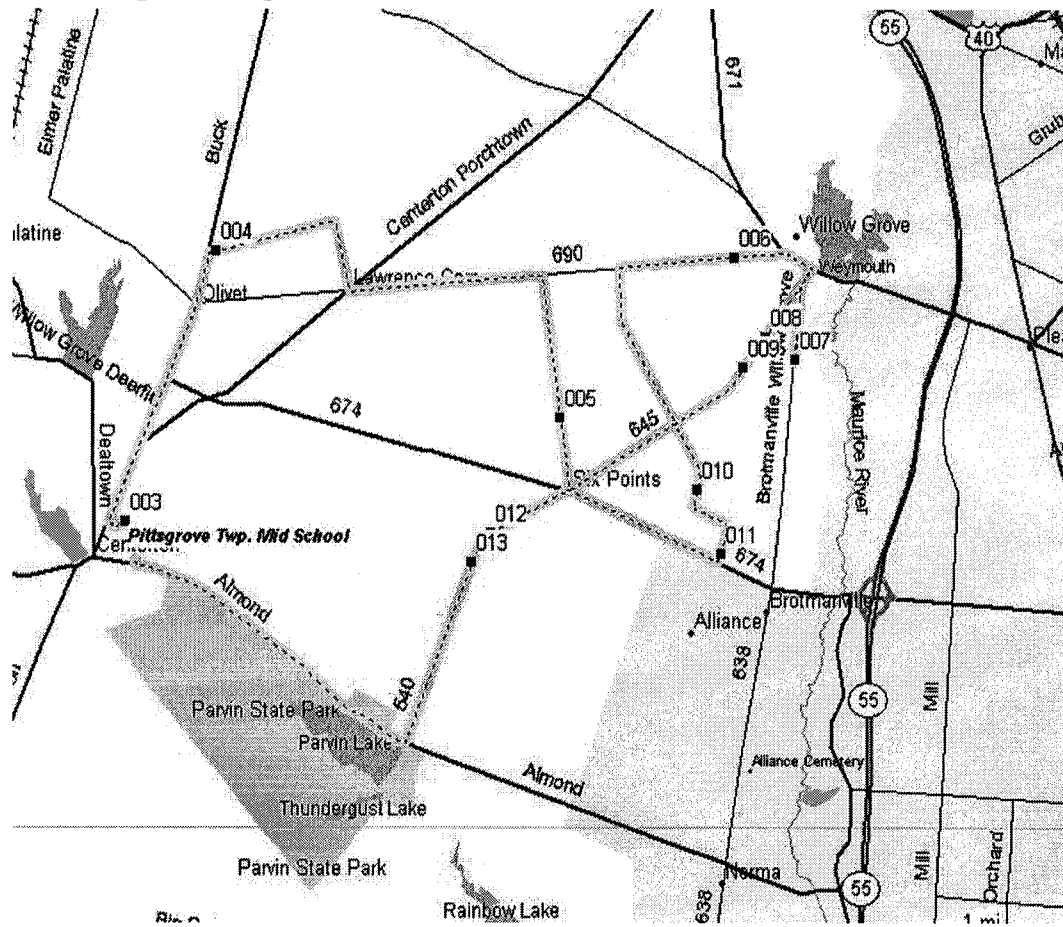


Pittsgrove School District Route 1



Pittsgrove School District Route 2

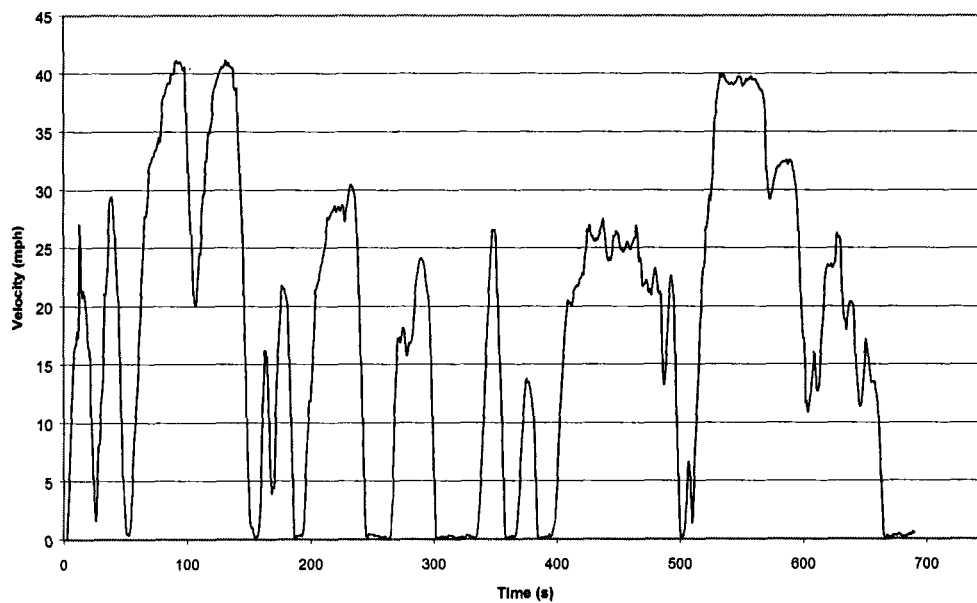
GPS Map of Pittsgrove, Route 2



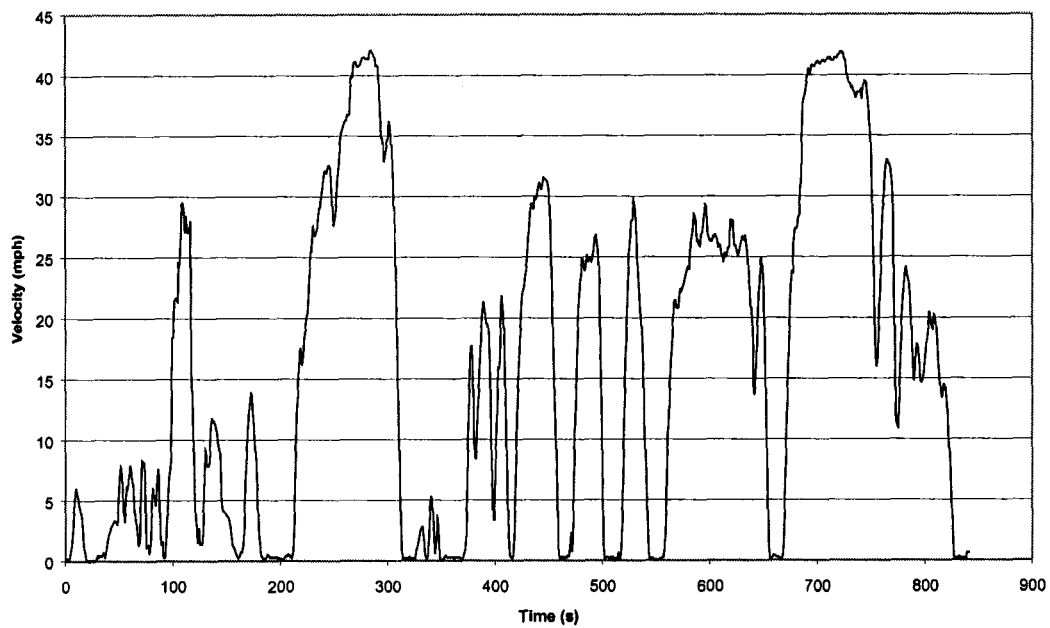
Pittsgrove Run 2 GPS Map

Prototypical School District 5: Deptford Township Raw Data

Velocity vs. Time (2 Unique Routes)



Deptford Township District Route 1



Deptford Township District Route 2